TUM School of Engineering and Design

Sustainable design and implementation of renewable energy systems in rural areas

Anna-Kaarina Seppälä, M.Sc.

Vollständiger Abdruck der von der TUM School of Engineering and Design der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktors der Ingenieurwissenschaften

genehmigten Dissertation.

Vorsitzender

Prof. Dr.-Ing. Rolf Witzmann

Prüfer der Dissertation

1. Prof. Dr. Thomas Hamacher
2. Assoc. Prof. Dr. Luiz Fernando Lavado Villa

Die Dissertation wurde am 31.05.2021 bei der Technischen Universität München eingereicht und durch die TUM School of Engineering and Design am 31.08.2022 angenommen

Abstract

Almost one billion people worldwide still lack access to energy, and the UN is aiming to bring them reliable power by 2030. The cost of extending the public electricity grid to rural areas has long been one a major barrier to achieving universal energy access, and renewable off-grid systems have rapidly risen in popularity as a sustainable cost-effective solution. Despite their potential, many factors still impede these systems from being universally adopted.

This thesis identifies and analyses the technical and socioeconomic barriers faced by renewable energy systems in rural communities, revealing that many of the current problems are those of lacking stakeholder organisation, local education and community involvement. Lacking power quality in existing solutions is identified as the main technical obstacle to widespread adoption. By means of thorough on-site surveys, interviews with numerous stakeholders in the area of renewable energy, as well as technical analyses of existing off-grid systems, a comprehensive framework is created to analyse individual locations for their suitability for renewable microgrid projects. Further, the use of load management as a solution to bad power quality is explored, and various algorithms are designed and compared based on the restrictions posed by their rural application.

Taking into account the identified barriers, a fully functioning solar-hydro prototype system is designed and implemented in a small village in North-East India.

Zusammenfassung

Fast eine Milliarde Menschen weltweit haben immer noch keinen Zugang zu Energie, und die Vereinten Nationen wollen ihnen bis 2030 zuverlässigen Strom liefern. Die Kosten für den Ausbau des öffentlichen Stromnetzes auf ländliche Gebiete sind seit langem ein großes Hindernis für den universellen Zugang zu Energie. Inselsystemeysteme, die auf erneuerbaren Energiequellen basieren, sind eine nachhaltige, kostengünstige Lösung, die in den letzten Jahren rasch an Beliebtheit gewonnen haben. Trotz ihres Potenzials hindern viele Faktoren diese Systeme immer noch daran, universell eingesetzt zu werden.

Diese Doktorarbeit identifiziert und analysiert die technischen und sozioökonomischen Hindernisse, denen erneuerbare Energiesysteme in ländlichen Gemeinden ausgesetzt sind, und zeigt, dass viele der aktuellen Probleme von mangelnder Organisation der beteiligten Interessengruppen, Bildung und Engagement der Bevölkerung stammen. Die mangelnde Stromqualität bestehender Lösungen wird als das wichtigste technische Hindernis für eine breite Akzeptanz identifiziert. Durch gründliche Umfragen vor Ort, Interviews mit zahlreichen Stakeholdern im Bereich erneuerbare Energien sowie durch technische Analysen bestehender netzferner Systeme wird ein umfassender Rahmen geschaffen, um einzelne Standorte auf ihre Eignung für erneuerbare Inselsysteme zu analysieren. Darüber hinaus wird die Verwendung eines Lastmanagementsystems als Lösung für die schlechte Stromqualität untersucht, und verschiedene Algorithmen werden basierend auf den Einschränkungen ihrer ländlichen Anwendung entworfen und verglichen.

Unter Berücksichtigung der festgestellten Hindernisse wird in einem Dorf im Nordosten Indiens ein voll funktionsfähiges Solar-Hydro-Prototypensystem entworfen und implementiert.

Acknowledgements

The list of people I need to thank for their support throughtout this thesis is probably longer than this report itself. Although the project was mine, I can't take credit for all its results. I had the privilege of working with some incredible master students who supported me throughout the project with their hard work and profound insight. The same applies to my colleagues, whose support was always abundant, and at times direly needed.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Nearly one billion people worldwide still have no access to electricity, and many more rely on fossil fuels such as diesel and kerosene which cause health issues and unwanted CO_2 emissions[1]. Lacking access to clean energy is not only detrimental to health and the environment, but also poses a substantial impediment to socio-economic and human development[2]. In 2015, 193 countries agreed to pursue new ambitious development goals to eradicate global poverty, hunger, disease and illiteracy by 2030[3]. For the first time, a specific target to provide universal access to affordable, sustainable and modern energy was included in the goals[4].
Between 2010 and 2020, significant progress was made in the global electrification growth, with a clear surge from 2015 onwards[5]. India is currently leading this process, having connected approximately half a billion people since 2000[4]. Nevertheless, contrary to the claims of Indian Prime Minister Narendra Modi[1], there are still around 210 million Indians without electricity access [6], constituting the largest unelectrified population in the world.

An estimated 35 per cent of those without access to electricity reside in developing Asia, while the majority (61 per cent) live in sub-Saharan Africa. Despite the increasing efforts to reach universal energy access by 2030, the latest World Bank projections suggest that this target will be missed by 650 million people[5]. The ever strengthening effects of climate change and population growth are likely to push universal energy access even further away from fulfillment.

Additionally to energy access being unevenly distributed globally, it also divides countries on a regional scale. Over 97 per cent of the world's urban population is already connected, while for the inhabitants of rural areas the figure is less than 79 per cent[7]. Due to long distances, sparse population and the often challenging geography of these remote regions, extending the national grid is strenuous and expensive, and the prospective financial gains are very small. Further, scattered unorganised groups with diverse needs are unlikely to wake much political interest on a national level, and are hence easily forgotten by policy makers[8]. The task of electrifying the poorest and most remote regions is referred to as last-mile electrification.

In remote locations, small off-grid systems could provide a reliable and cost-effective power source and improve the standard of living of the local communities[9]. Utilising renewable resources would minimise negative effects on the climate and provide health benefits as opposed to conventional fuels[10].The decentralised nature of off-grid solutions would reduce the cost of electricity in absence of transmission infrastructure, and minimise transmission

---

[1] Mr. Modi claims that India has already reached 100-per-cent electrification as of early 2018.

losses.

Currently, over 133 million people consume energy produced by decentralised renewable systems[11], and these solutions are gaining popularity in the public sector as well, supplying schools, health care services, etc. It is estimated that by 2030, renewable off-grid installations will constitute around 30 per cent of all new connections globally[4]. These predictions rely on the fact that many countries have started offering grants and other support schemes for renewable energy projects in remote regions.

Clearly, renewable stand-alone energy solutions have many advantages over conventional systems, and already play an important role in reaching universal energy access. Still, these technologies do not come for free, and often cannot be privately purchased by communities due to lacking funds[12]. Local governments, despite being eligible for the aforementioned support schemes, are often not aware of them, nor of the benefits of renewable technologies in general. But even in cases where a microgrid is successfully installed, it may fail in the mid or long term. Mistakes in the design or implementation might reduce the system lifetime, and failure to adequately assess the needs and wants of the local communities before installation might cause the system to fall into disrepair out of mere disinterest of the users[2]. Lacking sense of ownership or utility may also motivate people to abuse the energy systems [13]. Also, if the provided service is unreliable, and system power outages frequent, communities may prefer to opt out of connections rather than paying for such low-quality service[10],[14]. Further, electricity alone will not provide development, but new consumers will need to be made aware of productive use cases for it in order for them to benefit financially.

In order for the 193 countries that have adopted the Sustainable Development Goals to meet their 2030 deadline for universal energy access, various governments, international organisations and other public and private entities need to focus on the most feasible and fail-safe solutions available. Discovering which approaches have potential, and which factors need to be taken into account in order for these technologies to succeed, is paramount.

The creation and adaptation of new policies and laws are undoubtedly needed to push the Sustainable Development Goals further towards realisation[8]. However, many social, economic and technical aspects exist on a local level that affect the expansion of renewable off-grid solutions in rural regions. Identifying and addressing these factors helps advance rural electrification from a bottom-up perspective. By determining the barriers to renewable energy in their local context, individual organisations and electricity providers can increase the success rate of their specific electrification projects even in the absence of active political support. The more successful energy systems exist, the more interest will the surrounding communities have to implement their own.

This thesis set out to design and implement a successful renewable energy project in a rural location. The assumption was that by identifying the technical and socio-economic obstacles to the adoption of stand-alone renewable energy in the target community, the system design could be realised to address them early on, leading to a long-lived renewable microgrid with positive impact on the local community. To reach this goal, a myriad of surveys, interviews and other on-site studies were carried out in Nepal, India and Colombia. Further, different stakeholders from local community members to village leaders, company executives, scholars and local politicians were involved in the process of determining these barriers. It quickly became clear that the factors affecting renewable energy are not universal, as different regions have their own unique characteristics, and that no one-fits-all solution exists.

This thesis goes further than just identifying and analysing problems facing rural electrification. Based on the outcome of the analysis, a rural village in the remote regions of India was selected to implement a sustainable energy system pilot project, and, approximately a year later, the system was successfully installed. The design of the pilot system takes into account the most impactful factors affecting renewable energy as identified in the local context, and addresses them through technical solutions as well as active social involvement of the key stakeholders. Villagers and local leaders were tied into the project from the first site inspection and energy need assessment to the final installation and testing of the system. Many design assumptions made between the first visit and the installation proved infeasible during the deployment phase, but the flexible and modular system design, and having invested time to understand the culture and inner workings of the community allowed for changes to be made quickly and with the help of local experts.

During the assessment of factors affecting the advancement of renewable energy, one major technical barrier was identified: bad power quality. To mitigate issues due to it, a load management system had to be designed for the sustainable energy system pilot. However, clear limitations were set by minimal system cost, and robustness that are both necessary in the rural context. Thus, two very different load management systems were developed and compared to find a suitable one for the chosen application. The first is a simple rule-based control algorithm that reacts to changes in input power and load. The system relies on measurements and simply opens and closes switches in case the consumed load is higher than the allowed limit. The second load management algorithm is based on model-predictive control, offers more flexibility and integrates forecasting of the system state to optimally control power sharing within a microgird. Both approaches were tested and compared against the strict hardware and software requirements emerging from the necessity for low-cost and robustness. Cheap open-source microcontrollers were chosen as the implementation platform to ensure availability and low cost.

The ultimate goal of this thesis is not to propose a one-fits-all solution to rural electrification, but to offer a case study of how a successful renewable energy system could be installed under specific circumstances. However, this is not to say that the information contained within this thesis would not hold universally. Some of the lessons learnt are naturally highly subject to the local context, but others can undeniably be applied more broadly. Establishing a trusting relationship with the local community is an important example of the latter. Thoroughly understanding the needs and wants of the community is key to successfully implementing a sustainable microgrid, and having their support should not be taken for granted. Involving the villagers themselves in the decision making process gives them a sense of ownership, and taking part in the design and implementation educates them on how to operate and maintain the energy system. This being said, technical aspects such as modular design and stable power supply are also paramount for the long-livedness of the installed microgrid.

1.1 Organisation of thesis

This doctoral thesis is logically separated into three different parts. The first is dedicated to the topic of universal energy access, and the study of the factors impeding the advancement of renewable energy systems in rural areas. The history and necessity of providing universal energy access is evaluated by means of a literature survey, and subsequently, the factors currently impeding the poorest and most isolated communities from gaining access to energy are analysed. The methods of this analysis include carefully designed surveys, semi-structured interviews with experts and members of the studied communities, as well as technical inspections and power-quality assessments of existing installations. In order to interpret the results of the technical analysis, this part will also delve into what power quality is, and how it is defined.

The second part is directly linked to the first in that the outcome of the analysis of factors affecting adoption of renewable energy services in rural regions points to power quality as one of the most important technical obstacles for energy access. This begs the question of how power quality can be improved. This part gives an introduction to the concept of load management as a meant of power quality control. Subsequently, the limitations and requirements on load management systems as set by the rural application are presented. Then, two different load management strategies are presented and tested. These methods have been designed with financial and operational constraints in mind that are realistic for rural scenarios. Finally, the two methods are compared to determine which of them is more adequate to be implemented in a real test case.

The third and last part of the thesis details the process of planning, designing and implementing a renewable off-grid power system in the rural village of Jamupani in Arunachal Pradesh, India. The process was undergone taking into account the results of parts one and two, and serves to showcase the measures needed to realise a sustainable rural electrification project under the given circumstances.

It is important to note that although the organisation of this thesis is chosen in a certain way, all three parts of the project evolved throughout the three years of the projects duration. This means that some of the research questions emerged organically from the results of another, and that some decisions were made early on and adjusted in the light of new information from parallel work.

1.2 Problem statement and scope

Although many impeding factors are clearly social and socio-economic, the main emphasis in this thesis is given to bad power quality as an obstacle to universal energy access, and to the design of load management systems to mitigate it. This is simply due to my background as an engineer, which makes me far more qualified to tackle technical issues as opposed do social ones. However, as mentioned throughout this thesis, utmost care was taken to address social issues as well, as no degree of technical finesse is enough to keep a system running that has no benefit for the community where it was installed. Further, this thesis does not opine on which renewable technologies or which system architecture is the best for rural electrification scenarios. As based on the research conducted as part of this project, these technicalities depend fully on the available energy sources and the consumption patterns of

the local inhabitants.
The main goal of this thesis is to provide a case study of a successful sustainable energy system installation, from site selection to energy need assessment, system design and final implementation. The applied nature of the project means that many contributions and lessons learnt are practical rather than theoretical, and anecdotal instead of highly statistical. Nevertheless, I hope that other researchers and especially microgrid providers find value in them to further promote renewable energy in the rural context.

1.3 Research questions

There were three concrete research questions that motivated this research, and they are listed below:

1. How can a renewable energy system be implemented in a sustainable manner in a rural area?

   This is the principal question to be answered. From the very beginning, it was clear that this question would not have a universal answer, so it was decided to pursue answering it in the form of a case study, i.e. for a specific location, and by designing and implementing a renewable energy system from scratch.

2. What are the factors inhibiting the advancement of renewable energies in the rural context?

   This question naturally follows the first, as, in order to find ways to successfully implement any technology, the challenges facing it must be first identified and analysed. It was decided to carry out this analysis on a selection of locations to gain understanding on regional differences. Further, the difficulties faced by other similar new technologies were studied to obtain a comparison. This question was to be answered in the form of thorough survey studies as well as interviews with community members, microgrid operators and other important stakeholders involved in the renewable energy sector. Here, the original assumption was that the obstacles to renewable energy would mainly be technical in nature. However, during the literature reviews and on-site studies it became clear that socio-economic aspects play an essential role in the issue.

3. Which load management strategy should be used in a rural microgrid?

   The question of load management emerged as a result of the initial literature review as well as the findings of two extensive surveys in India and Nepal. During this research, bad power quality was identified as the single most impactful technical barrier to renewable energy systems in rural areas, which was further enforced by on-site measurements of Nepalese off-grid installations in a further study. It was thus clear that this problem should be addressed in a successful energy system implementation, and it was decided to design two very different load management algorithms and to compare them against common requirements to choose the most appropriate one.

These three questions are very broad and served the purpose of guiding the research presented in this thesis towards the implementation of a fully working renewable energy system in rural India.

1.4 Contributions

This thesis identifies factors negatively affecting the advancement of renewable micorgrid projects in the rural context. Social, economic and technical issues are found and analysed. The findings from two Indian states are compared with those obtained from rural Nepal and Colombia. Additionally, the current energy need is assessed in remote villages in India and Nepal.

The issue of bad power quality is addressed by proposing two load management schemes that are easily implementable on low-cost hardware, and realise power sharing tasks within a microgrid. The proposed schemes are compared in terms of ease of use, robustness, and cost.

A sustainable renewable energy system was designed and installed in the village of Jamupani, in Arunachal Pradesh, India. The system installation comprises one of the designed load management systems, and addresses many of the identified factors negatively affecting renewable energy adoption. At the time of writing, the system has been operational for over ten months, with evidence of surrounding villages taking measures to build their own systems based on the Jamupani model.

Due to the applied nature of this thesis, many of the contributions are practical and anecdotal instead of theoretically based. Many of the lessons learnt apply to the specific context of Jamupani, but many more bear significance more broadly as well. It is my sincere hope that this report will serve other researchers and organisations promoting renewable energy systems in rural regions of the world.

Part I

Assessment of energy need and barriers to renewable energy

Chapter 2

Universal energy access

In 2015, the United Nations adopted 17 Sustainable Development Goals (SDGs) to "achieve a better and more sustainable future for all". The UN member countries agreed to work towards achieving 17 ambitious goals by 2030, including reducing inequality, eradicating famine and illiteracy, and providing universal access to clean energy. This last goal is called goal 7: affordable, reliable, sustainable and modern energy, and comprises the following targets[15]:

1. By 2030, ensure universal access to affordable, reliable and modern energy services
2. By 2030, increase substantially the share of renewable energy in the global energy mix
3. By 2030, double the global rate of improvement in energy efficiency
4. By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology
5. By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support

Energy is an essential part of human life today. It is so intertwined with how we live, how we work, and how we feed and entertain ourselves, that it is hard to imagine what life would be like without it. The role of energy in increasing income and well-being is indisputable, but so is its impact on the environment. Unfortunately, many of the regions that are hit the hardest by climate change are home to those with limited access to energy themselves. Universal energy access is key to lifting communities out of poverty, malnutrition and disease, but it needs to be achieved in a sustainable manner. Currently there are still roughly three billion people without access to clean cooking technologies, and exposed to harmful levels of air pollution. Further, approximately one billion people lack access to electricity with negative repercussions to their daily lives. These are the people targeted by the UN sustainable development goal 7[15].

2.1 Rural electrification

Rural electrification is the act of providing decentralised power supply to remote regions out of reach of the national grid[16]. These areas are often marked by challenging terrain, bad infrastructure, sparse population and wide-spread poverty, making them unappealing targets for government efforts and private companies. Approximately 97 per cent of the world's urban population already has access to electricity[17], making the mission to electrify rural regions one to achieve universal energy access.

2.1.1 History

Electrification started in the late 19^{th} century in Britain and the United States, quickly spreading to other Western countries as governments began to build their respective national grids[18]. This process naturally started from major cities and well-connected areas, expanding quickly towards more remote parts of each country. By the 1930's, Europe and North America had connected most of their population to the grid, and their focus shifted to providing electricity access to the rural communities as well.

Developing countries followed the example of electrification with some delay. By the 1990's, when most of the Western nations had already reached full electrification, many countries in Latin America, Africa and Asia were still struggling to provide power to their urban population, let alone their rural communities[19][20]. As an example, figure 2.1 provides a comparison between urban and rural energy access in India between 1993 and 2017.

As mentioned previously, we are far from achieving universal energy access. Almost one billion people still lack access to electricity, and roughly three billion have no access to modern cooking technologies. Process is still being made, and new, cleaner technologies allow for more sustainable form of electrification to take place even in the most remote areas. Still, numerous financial, technical, political and social issues need to be solved on local, national and global levels to achieve universal energy access[21].

2.1.2 Benefits

Universal energy access would provide remote communities with income-generating opportunities. Electricity can help create jobs in sectors that would not exist without it, such as printing services, internet cafes, or even replacement services and retail of electronic components. Restaurants and food stalls would benefit from refrigeration, and farmers could irrigate their fields and improve their yields[8]. Irrespective of the one's trade, improved access to energy offers an economic benefit.

Energy does not only boost the local economy, but can also help tackle complex social issues. This is clear especially in the sector of clean cooking, as the task of preparing food predominantly falls under the responsibilities of women in many cultures. This also means that the health issues associated with traditional cooking methods principally affect the female population. Further, gathering firewood for cooking is often a time-consuming task that mostly women and children need to carry out. Replacing traditional fuels with electricity, biogas or LPG would free women to study and work, improving their social status, and providing necessary

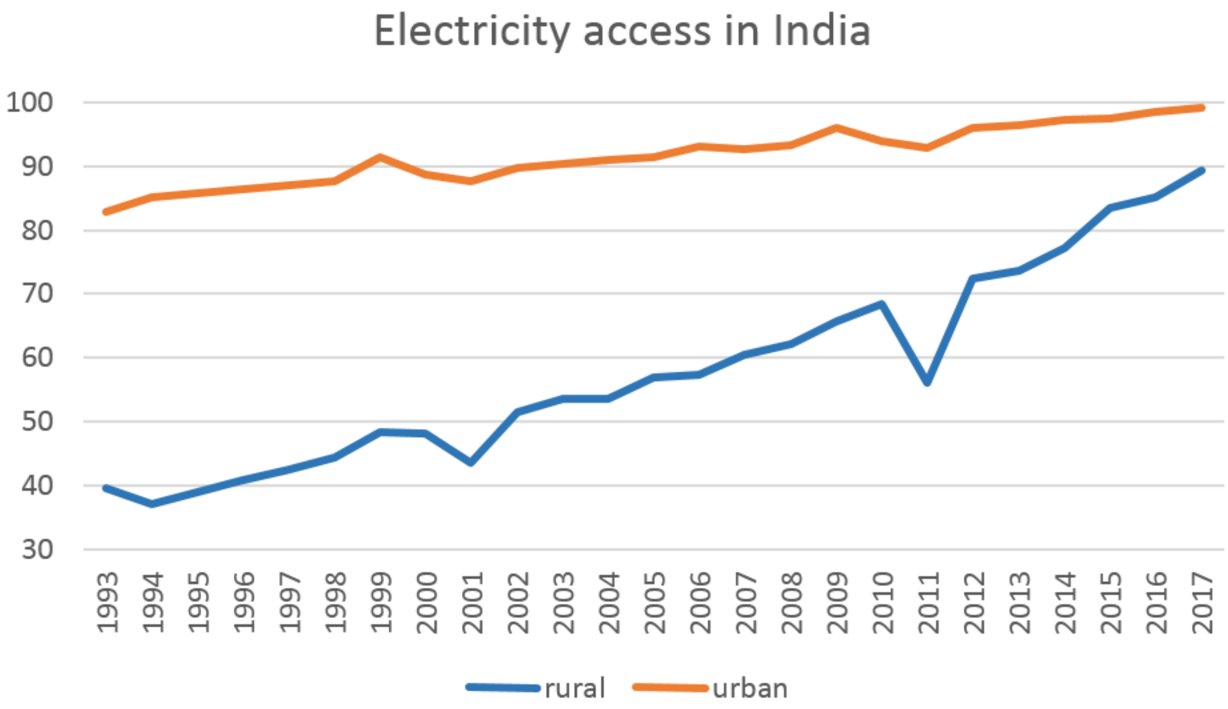


Figure 2.1: Access to electricity in India over time, shown in per cent.

steps to achieve gender equality[8].

2.1.3 Recent trends

Between 2010 and 2020, significant progress was made to improve the global rural electrification rate, as shown in figure 2.2. From 2015 onwards, the rate at which communities are gaining access to electricity has clearly accelerated[5]. India is currently leading this process, having connected approximately half a billion people since 2000[4].

The shift from traditional fuels to renewable energy sources has become evident in the rural electrification sector since the turn of the millennium. The current consensus is that renewable off-grid systems are the key to sustainably accomplishing the last-mile electrification targets until 2030, as set by the UN[8][21][15]. By using locally available resources, the hurdle of obtaining fuel despite bad transport infrastructure can be mitigated, and renewable energy systems are cheap and environmentally friendly to operate.

Despite their recent rise in popularity as a means of rural electrification, some renewable energy sources such as solar and wind power can have high investment costs associated with them[8]. Their intermittent nature can cause severe power quality issues if not controlled adequately [22], and extensive battery systems are often required to ensure that power is available at times of peak demand. These factors can cause a significant increase the hardware costs.

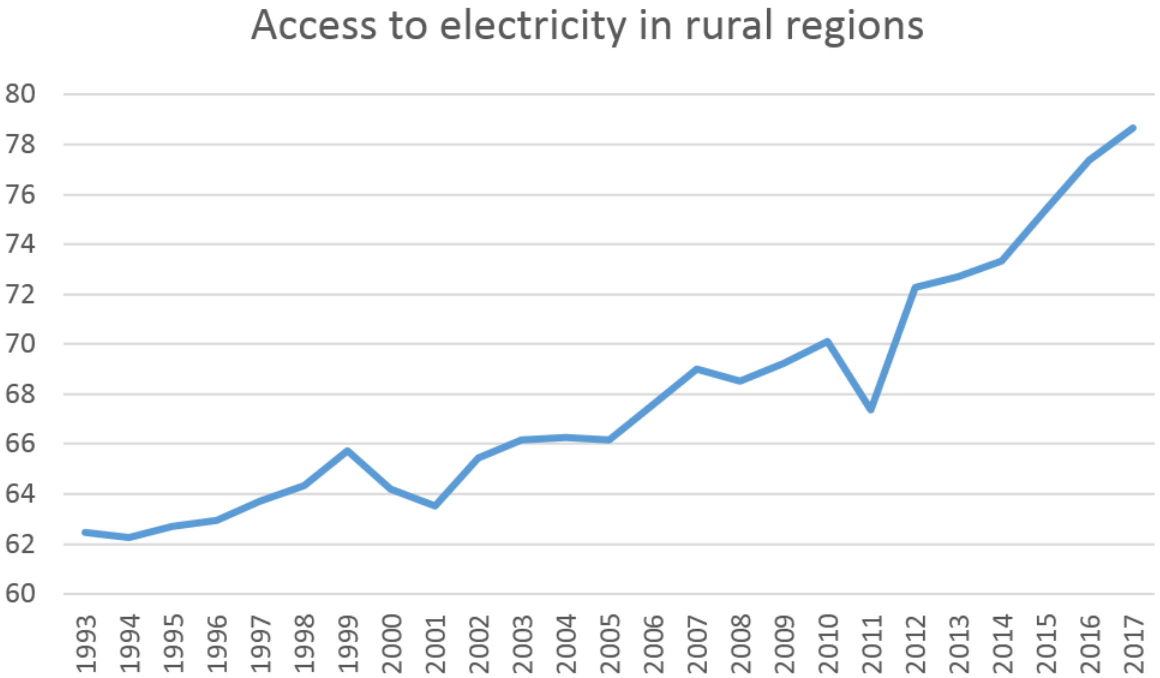


Figure 2.2: The percentual global rural electricity access over time.

2.2 Indian context

The pilot energy system designed and installed as part of this doctoral thesis is located in Arunachal Pradesh, India, and hence, it was deemed necessary to give more context to the state of rural electrification in India in general.

India has actively pursued to electrify the small percentage of its population still living without connections. The Saubhagya scheme was launched in September 2017 with the aim of providing electricity connections to all Indian households, installing them free of charge for those below a certain poverty limit[23]. However, as of 2018, India's Prime Minister Narendra Modi claims that India has already reached 100-per-cent electrification. This has been regarded by many as a mere publicity stunt to boost his re-election campaign as there India is still home to around 210 million people without electricity access [6], constituting the largest unelectrified population in the world. Further, the scheme has been criticised for only adding connections without providing sufficient, or any, power to the consumers[24].

The Indian Government's definition of energy access is ambiguous and allows for it to declare full electrification status with millions still unconnected. According to the definition, in order for a village to obtain the status of electrified, "basic infrastructure such as distribution transformer and distribution lines are provided in the inhabited locality. . . and electricity is provided to public spaces like schools, Panchayat[1] office, health centers, dispensaries, community centers etc.; and the number of households electrified are at least 10% of the total number of households in the village."[25]

Clearly, this definition could leave 90 per cent of the village in the dark. Government-level

---

[1] Panchayat is the self-governed village council of a rural community.

definitions like this can be detrimental to achieving universal energy access if subsidies are provided only to fulfill the minimum requirements. In fact, as explained in chapter 3, many rural villages in India struggle to get government support for their electrification schemes because, according to the above definition, they already have electricity. This was found to be the case even in some villages where not a single building had a working electrical connection.

2.3 Note on the research of this thesis

The main goal of this thesis was to successfully implement a sustainable, robust renewable energy system for a rural village in India. In order to realise an energy system in a sustainable manner, multiple factors need to be taken into account. No one-fits-all solution may be expected, as the energy needs of rural communities are as diverse as the locations themselves. For instance, it is intuitively clear that installing a hydro-power system only works in areas where water is abundant, and the same idea applies to other aspects of an energy system as well. The need for storage, the system capacity, operation and maintenance schemes, and the overall feasibility of a system all depend on what the end-users need and want, what energy sources are available, and what the cultural context is.

The rest of part I describes in detail the scientific work done to understand the current technical and socio-economic obstacles to the advancement of renewable energy systems in rural areas. This research comprises on-site energy demand surveys conducted in villages of various stages of electrification, expert interviews with multiple stakeholders in the rural electrification and clean cooking sectors, as well as measurement and analysis of the technical capabilities of existing off-grid energy systems.

The studies are introduced on a case-by-case basis, and grouped into three chapters representing the above-mentioned topics. The findings are discussed at the end of each chapter, and part I is ended with a common conclusion logically tying the results together.

Chapter 3

Assessment of energy need

The energy need of rural communities must be thoroughly assessed in order to design a sustainable off-grid energy solution. Only by knowing what the target community wants and is willing to pay for, can a microgrid be designed and deployed appropriately. Further, the potential impact of the system must be estimated to ensure that it affects its end-users in a positive manner.
The energy need of rural communities was assessed in Nepal and in India. In both cases, a number of villages with different socio-economic profiles was identified for a survey-based study. In Nepal, the focus was given to three districts across the country, each receiving power from a small-scale hydro turbine. The India survey was wider in scope, comprising multiple electrified and non-electrified villages in two states, namely Uttar Pradesh and Arunachal Pradesh. The methods and results presented in this chapter are for the most part based on the work of the following students: Nabin Gaihre, Rinald Pereira, and Sudhir Jha.

3.1 Energy need in rural regions of Nepal

The survey conducted in Nepal served the purpose of analysing the energy need in the rural districts of Bajhang, Panchtar and Kavrepalanchok. The first of the three districts situated in North-West of the country, whereas the other two are located more towards the South-East. 30 households per district were surveyed, resulting in a total sample size of 90. Further, the households in each location were chosen by random sampling. The visited districts are shown on the map in figure 3.1. The study was realised in the Autumn of 2017.

3.1.1 Method

This study was carried out in the form of a in-person survey in different communities across Nepal. The questionnaire used in the study gathered data on socio-economic factors of each household as well as energy need. The acquired household information included household size, yearly income, educational level of all family members, occupation type of the head of house, and other economic activities. The energy need assessment was based on details on current use patterns of common electrical appliances, the number of appliances in each household, and wishes expressed by the interviewees on obtaining more appliances. The monthly household energy consumption was determined based on the number of electrical

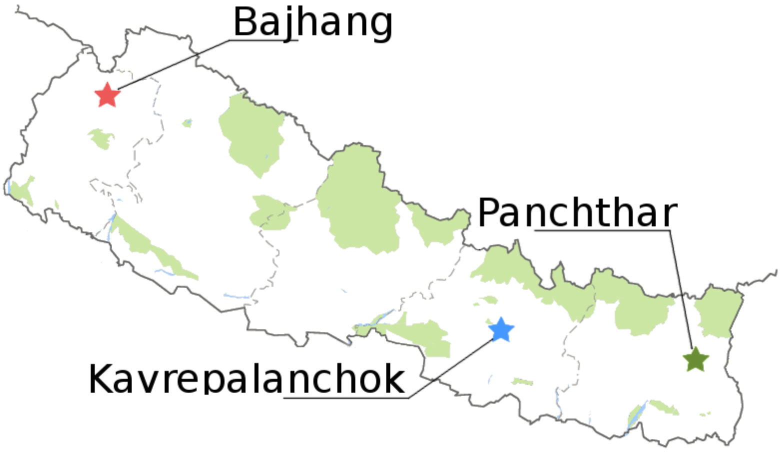


Figure 3.1: Location of Bajhang, Kavrepalanchok, and Panchthar on the map. Own illustration, map data from Google [26].

appliances used within each household and the hours of use (per day) of said devices, as reported by the families. Additionally, questions were posed about the families' satisfaction with the available electricity services in terms of power quality, about the households' monthly expenses on energy services, and monthly consumption of cooking fuel.

It is well reported that survey data does not always provide accurate information. Especially people at the receiving end of a service tend to answer questions in ways that please their interviewers, thinking that certain answers would benefit them in some manner. Some people are uncomfortable with answering direct questions about their wealth, and try to belittle their income or otherwise lie about it. Some information given is false simply because those asked do not know the right answer, and if there is no way of directly measuring or categorising something. This may occur when asking about daily appliance usage, for example, as few people know exactly how long they keep their lights on per day, and so on. Therefore, surveys should not be used as a source of exact numerical data, and are better suited to show trends and comparisons.

Various ways to mitigate these problems were used as part of the survey. Indirect observations were made to validate the interviewees' answers against the reality. As a simple example, if a family says they have very little income but clearly own the newest phones and a lot of cattle, there is reason to question their statement. Another way to improve the quality of answers is to give the interviewees simple options. For instance, the questionnaire used in this study included simple ranges for income (less than \$1,500/year and more than \$1,500/year), making this question less intrusive for the interviewees.

The survey was conducted as a series of personal interviews with the household members. The number of electric appliances was checked by manual inspection, and local assistance was used to initiate contact and translate in case families only spoke their local language.

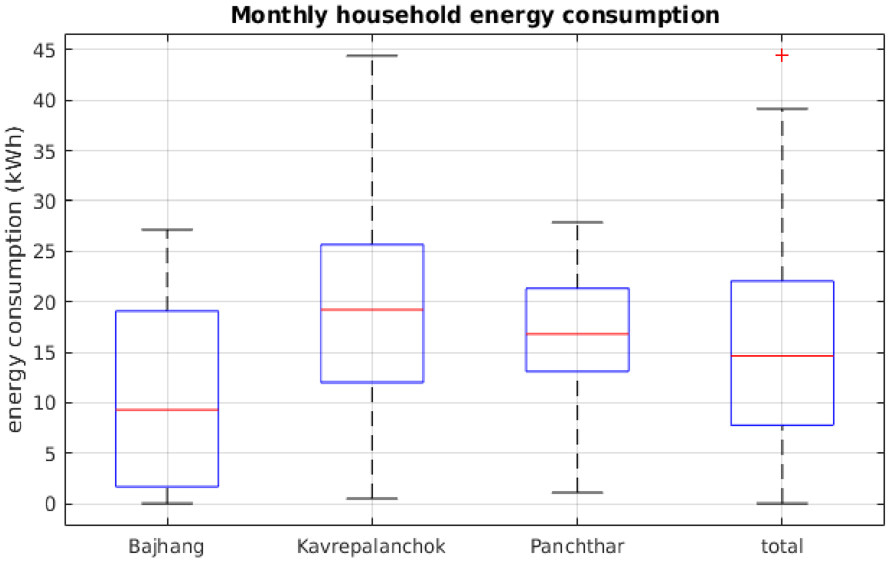


Figure 3.2: Boxplot of the monthly energy consumption in Bajhang, Kavrepalanchok, and Panchthar.

3.1.2 Results

Nepal has one of the lowest energy consumption figures per capita in the world[27]. It has very few reserves of oil, gas and coal, thus making it reliant on expensive imports and biomass-based fuels to cover its growing energy demand[28, 29]. Further, over 80 per cent of the population in Nepal live in rural areas[30] where long distances and challenging geography complicates the extension of the national electricity grid.

This survey determined the energy need in three rural districts of Nepal. The average monthly household electricity consumption in the surveyed districts was found to be very low. For Bajhang, Kavrepalanchok, and Panchthar it was 10.7 kWh, 19.6 kWh and 15.6 kWh, respectively. A boxplot of the monthly energy consumption is provided in Fig. 3.2. For reference, the average U.S. residential utility customer had a electricity consumption of 897 kWh per month in 2016 [31].

Households in each region were found to typically use electricity for lighting and entertainment only, using conventional fuels like firewood and lpg for cooking. The most common household appliances across all regions were lights and and old CRT televisions. Bajhang faired worst in terms of access to electricity, with 10 per cent of surveyed households without an electrical connection. This was not necessarily due to lower income, and the affected families were found to own electrical devices such as mobile phones despite not having electricity. They charge their appliances at their connected neighbours'. Bajhang was also found to have fewer literate adults, fewer households of higher income, and fewer TV's than Kavrepalanchok and Panchthar. Fig. 3.3 shows the relative access to various lighting types for each district, while other appliances along with household income and adult literacy rate are plotted in Fig. 3.4.

Over 85 per cent of all surveyed households pay a fixed minimum charge of 80 Rs. (€ 0.78) a month, irrespective of their consumption. Therefore, no real correlation between the two exists, and people have no economic incentive to control their power consumption. A good example of this are households with incandescent light bulbs. These are usually cheaper than the more modern LED lamps[1] or CFL's, and thus still popular in rural areas. Due to their high power consumption, however, some lower-income households with no other appliances still have spectacularly high monthly energy demand. Seeing that over 30 per cent of surveyed households own incandescent lights (see Fig. 3.2), it is obvious that the current power shortage problems could be minimised by simply replacing all existing incandescent bulbs (60W-100W) with LED lamps (5W). But as the monthly charges do not correlate with energy consumption, low-income families are unlikely to update their light bulbs.

As a direct consequence of the power shortage, many households are unsatisfied with the grid quality, experiencing voltage fluctuations when plugging in devices, and frequent blackouts due to excessive load. The number and type of appliances used is directly governed by the evident power capacity shortage in all surveyed districts.

The limiting behaviour of the power shortage can be seen in the households' desire to acquire more appliances. Fig. 3.5 shows the interviewed families' desire for various electrical devices. A TV is a desired appliance in households that do not own one, but electrical cooking devices obviously form a rising trend. Only 10 per cent of sample households currently possess a rice cooker but 84 per cent wish they had one. Seeing that over 80 per cent of all surveyees belong to a higher income group, money clearly is not the limiting factor, but rather the lack of power. Additionally, when asked what type of energy system ownership scheme they prefer, 87 per cent of the families chose communal ownership over private-owned systems. This suggest that capital cost and maintenance of private systems are an issue.

The main indications of this study are that the current power shortage in the rural regions of Nepal is limiting the development of these areas, and that the existing business models for

---

[1] According to survey results, LED lamps in Nepal may be up to ten times more expensive than incandescent ones.

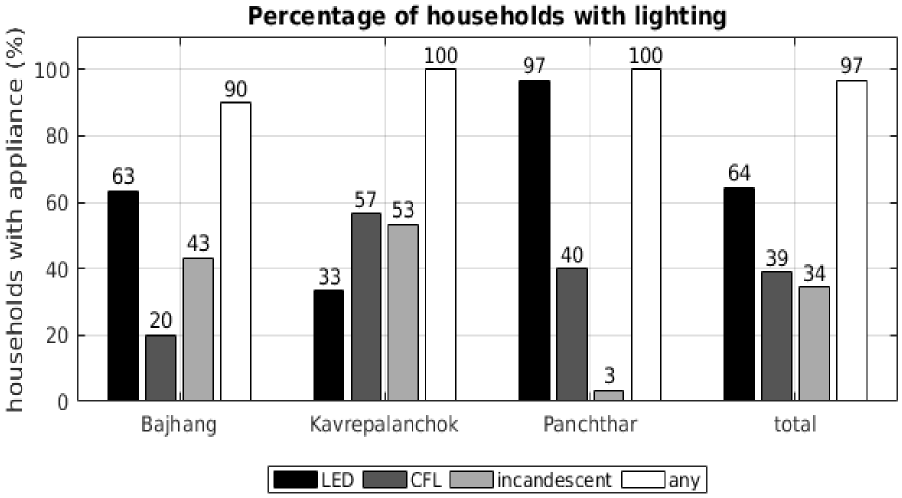


Figure 3.3: Percentage of households with lights in Bajhang, Kavrepalanchok, and Panchthar. The label 'any' refers to households having any of the three light sources.

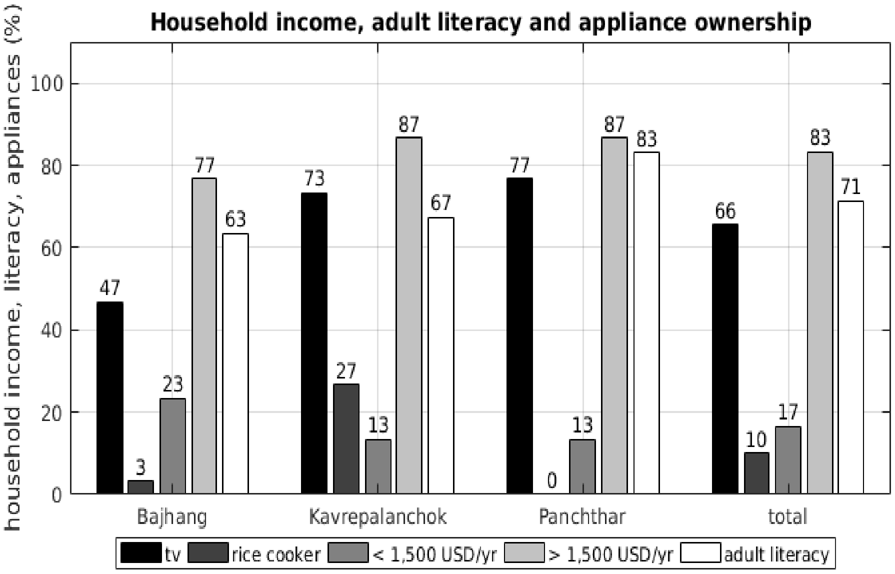


Figure 3.4: Percentage of households with TV or rice cooker. Relative distribution of household income and adult literacy is also plotted.

electricity provide no incentive for the households to monitor their consumption. The energy demand is far greater than the installed capacity, but at the same time it is infeasible for low-income families in particular to upgrade to more efficient devices in order to save energy. Due to their high power consumption compared to other devices, the introduction of rice and induction cookers into the surveyed districts is hindered. This is significant because they would free women and children from gathering firewood and thus give them more time to do paid work and to study.

3.2 Energy demand assessment in rural communities of Arunachal Pradesh and Uttar Pradesh, India

In this study, multiple villages of varying stages of electrification in Arunachal Pradesh (AP) and Uttar Pradesh (UP) were surveyed. The aim was to determine the energy need across two demographically very different states and to provide an overview of the possibilities for stand-alone microgrids in these regions. The focus was on non-electrified villages, but partially and fully electrified communities were included as a reference. The survey consisted of three questionnaires, one aimed at households, one at village heads and one specifically for schools. The study was conducted between May and July 2018.

3.2.1 Method

Two categories of electrical energy consumption were defined; consumptive usage and productive usage. The former comprises all use contributing to improved comfort within a household but not helping to generate income. The latter entails use cases promoting economic activities [32]. Thus, it also comprises endeavours improving education and health because both have positive implications on income [33]. Table 3.1 summarises these definitions.

The presence of productive use cases is linked to communities' ability to pay for or maintain off-grid power systems. Both categories may be extended by energy demand that could be covered by electricity in the future. Hence, if a village has an active workshop where all mechanical repairs are currently done manually, it is probable that the workers will adopt electrical machinery when power becomes available. Such a scenario makes building an off-grid system more viable than one where only consumptive use patterns are present.

To understand consumptive and productive electricity demand, and assess possible future trends, a survey was created and subsequently carried out in Indian villages of various degrees of electrification. AP and UP were chosen as the study sites for their low electrification rate, the remote location of villages and, in the case of AP, the challenging terrain. It is improbable that the surveyed communities would receive access to the national grid in the foreseeable future. Further, the differences in terms of the geographical and socio-economical characteristics of the two states guarantees a more general view of the electricity demand in India. In total, 73 households in 15 villages across AP and UP were surveyed, with 10 in the former and 5 in the latter. The total population covered by the study was 410. Additionally, one non-electrified

Table 3.1: Classification of electrical energy usage.

Use case	Description	Example
`Consumptive`	No income-generating potential.	Usage of household appliances, such as mobile phones and TV sets
`Productive`	Positive impact on income (direct or indirect).	Electric milling, usage or sowing machines (direct), improved learning conditions (indirect)

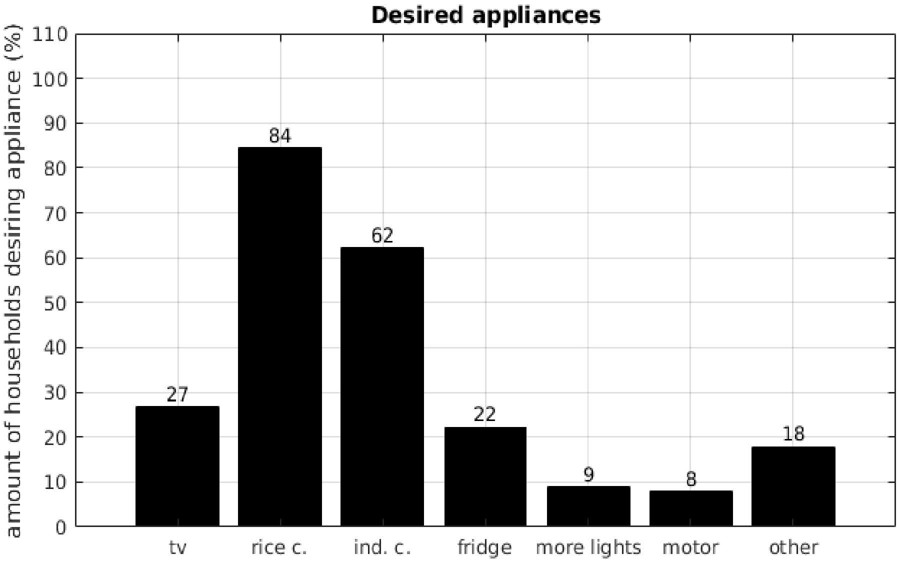


Figure 3.5: Percentage of surveyed households wanting various appliances.

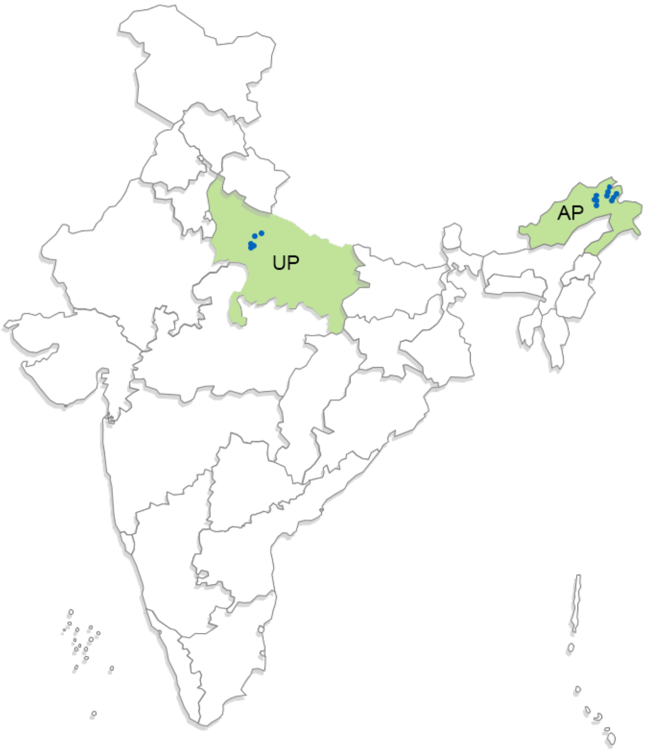


Figure 3.6: Location of the surveyed villages on the map of India. UP stands for Uttar Pradesh and AP for Arunachal Pradesh, and the blue dots represent villages.

governmental residential school in AP was included in the survey.

The visited villages may be organised into four different categories according to their level of electrification: Non-electrified (NE), microgrid electrified (ME), partially electrified (PE) and fully electrified (FE). Table 3.2 shows the definitions of each electrification category. Villages with no access to the national grid nor microgrids were deemed non-electrified, although some households may own private solar installations. 10 such villages were surveyed. Figure 3.6 shows the location of the surveyed villages on the map. Two microgrid-electrified villages were included in the survey. Typically these villages have tier 1 electricity access[2] provided by a microgrid company. The visited ME locations have been provided electricity access by the company Mera Gao Power[3]. Partially electrified villages are those connected to the national grid but without regular access to electricity. Power only becomes available if there is surplus in the grid. One such location in UP was surveyed, but additionally, two mainly NE villages were found to have individual PE households.

PE and FE villages were included in this study to provide a reference for energy need and were chosen in the vicinity of the unelectrified communities visited. Surveying villages with similar cultural and demographic characteristics allowed for a better estimate of the future trends in energy use in communities new to electricity access. Additionally, the governmental residential

---

[2] According to the definition of the World Bank, tier 1 electrification corresponds to households with access to very low power (minimum 3 W) for at least 4 hours per day [34].

[3] Mera Gao Power have provided each household in the surveyed villages with a 7 W connection that allows them to power 1 W LED lamps and a mobile phone charger.

Table 3.2: Village categories by electrification status.

Category	Description
`Non-electrified (NE)`	No access to national grid or microgrid.
`Microgrid electrified (ME)`	Tier 1 electrification by microgrid.
`Partially electrifed (PE)`	Sporadic access via national grid.
`Fully electrified (FE)`	Regular access via national grid.

school in Jamupani, AP, was surveyed for its significant impact on the village economy, and because it represents an additional (indirect) productive use case for electricity. Schools in other communities were closed at the time of the survey, and their productive use cases were assumed to be similar to Jamupani.

Children from Jamupani and neighbouring villages study free of charge and receive two to three free meals a day, which is a significant relief to many households relying on sustenance farming, and some villagers work at the school as peons and caretakers. Further, receiving education will have a positive impact on the future income of the pupils and their families. The survey was conducted on two separate levels to ensure the integrity of the gathered information. Firstly, household-level questionnaires were used to acquire detailed information of the energy need and appliance usage patterns of individual families across the surveyed villages. The second survey level (focused-group discussions) consisted of various village stakeholders such as village heads, school headmasters and the respected elderly that were able to provide a top-down view of the energy needs and use cases in the studied communities. These top-down discussions were necessary to better understand the potential of microgrids in the community. The surveys were carried out in interview form with an average duration of 30 minutes per household visit. Questions were mainly asked in Hindi or English in the presence of a local guide fluent in the regional language. Answers were jotted down by the research team and each questionnaire was given a confidence level based on the perceived trustworthiness of the interviewees [4].

The household-level questionnaire was structured as follows: First, demographic and occupational details of each household was enquired, after which household expenditure on alimentation, education, energy, etc. was determined. Then, the electrification status of the household was established based on ownership of electrical appliances and their daily usage pattern. Finally, the interviewees were asked to rate the importance of electricity in their lives and to give an upper limit for what they would be ready to pay for a reliable connection.

The focused-group discussion questionnaire included more open-ended questions about the general quality of life in the community. Information was gathered on topics such as housing, village economy, access to water, education and banks. The potential of biomass, hydro and solar based energy production was also discussed, along with possible productive use cases within the community. The provided answers were also used to verify some of the results of the household-level questionnaire.

---

[4] There is a body of anecdotal evidence on the fact that people are prone to modify their answers based on what they think might benefit them, especially in the development aid context [2], [35]. Thus, it is essential to assess the confidence level of acquired answers.

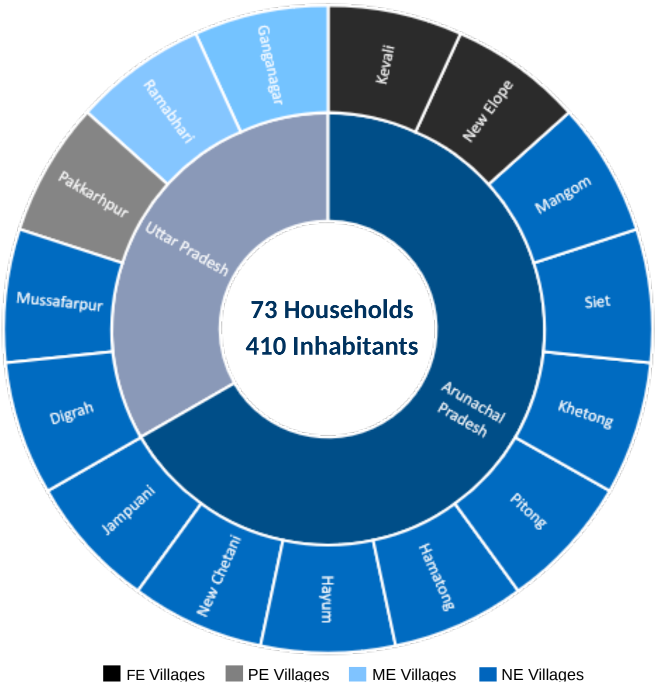


Figure 3.7: Overview of surveyed villages and their electrification status.

3.2.2 Results

The energy need survey in India was conducted in two immensely different states, Arunachal Pradesh in the North-East, and Uttar Pradesh in the North. With 13 people/sq.km, Arunachal Pradesh (AP) has the lowest population density of all states of India [36]. Due to its few inhabitants, mountainous terrain, extending the national grid to AP is strenuous and expensive, and has thus largely been neglected. The state has a huge hydro-power potential that to this day has failed to provide electricity locally [37].

The demanding terrain makes transport within AP extremely difficult. Only few paved roads exist and landslides are common in the mountains. The local economy is based on agriculture and the manufacturing sector is limited [38]. Thanks to the abundance of water, irrigation is mostly not needed.

Uttar Pradesh (UP), with almost 200 million inhabitants, is the most populous state in India [39], [40]. Its geography is marked by vast plains of the Ganges river. The state suffers from a dire electricity shortage and a low adoption rate for connections even when the grid would be available [10]. Electricity access growth in UP has failed to keep pace with population growth. UP's main source of income is agriculture based on seasonal crops such as rice, wheat and sugarcane. Thanks to UP's more developed transport infrastructure, farmers have good access to fertilisers and modern irrigation technologies [39]. In the dry season, temperatures up to 50 centigrades are reached and irrigation becomes essential. Refer to figure 3.6 to see both states on the map.

As stated in section 3.2.1, villages of varying degrees of electrification were surveyed to obtain a more reliable result, and figure 3.7 gives an overview of the visited villages and their state of electrification. The results discussed in this section only concern NE and ME villages as defined in table 3.2, unless indicated otherwise. These are the main categories that are interesting from the point of view of sustainable microgrids.

In AP, villages are typically very small and remote, and the number of households included in the survey ranged from two to around 20. The average household size for NE and ME villages was 5.44 members. Around 94 per cent of the surveyed households were found to do sustenance farming, relying on cash crops such as cardamom, yam or opium for extra income. 15 per cent of interviewees also do other manual labour such as head-loading goods.

In UP, the size of villages is far larger than in AP, typically over 100 households. Also the average household size was found to be larger at 6.67 members per family. Further, 42 per cent of surveyees in UP were employed as labourers and 63 per cent cultivated seasonal crops like sugarcane, wheat or maize for their income. These categories overlap as some households have multiple sources of earnings.

The average monthly income of the surveyed NE and ME households across both states was ₹ 10,522 (€ 124.9), resulting in an average per-capita annual income of ₹ 21,783 (€ 290.6). This value is 81 per cent less than the national average [41]. In AP, the average monthly income was found to be significantly higher (at ₹ 11,471) than in UP (₹ 8,269). This is mainly because of the high-value crops cultivated in AP.

NE and ME communities rely heavily on alternative sources for light and electricity. These include kerosene lamps, batteries, firewood, solar home systems (SHS) and solar lanterns. Especially in AP, solar-home systems and electric torches are immensely popular, with 62 and 95 percent of the households using them, respectively. In UP, the corresponding figures were found to lie at 28 and 44 per cent. Instead of torches, many UP households were using the flashlight application on their mobile phones.

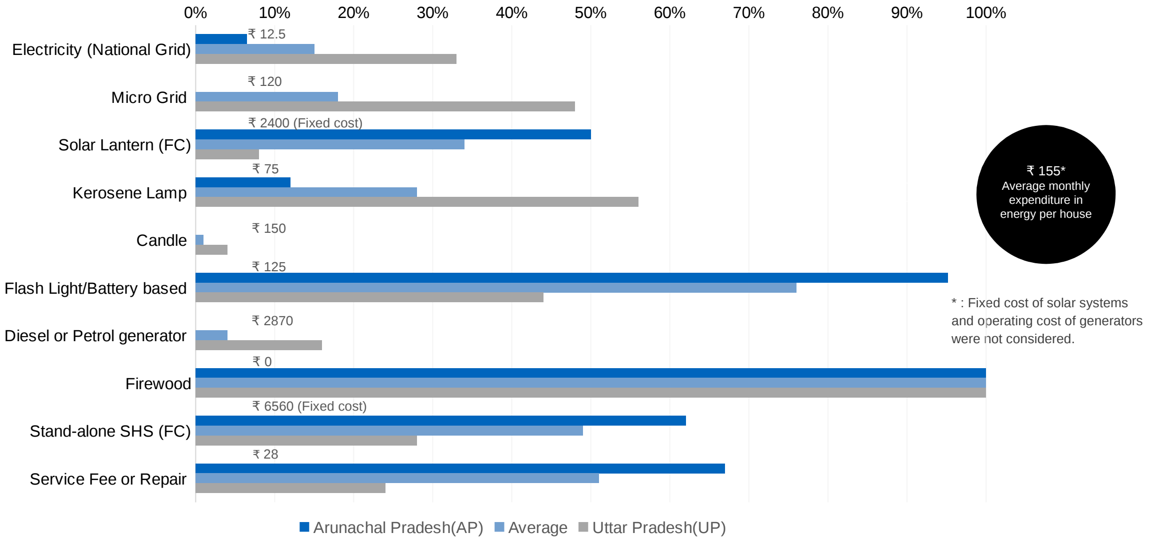
Every household across both states was found to use firewood on a day-to-day basis. The reasons for this are multiple; Firstly, firewood is readily available and free of cost, although some members of the household need to invest time in gathering it. Secondly, a fireplace within the home is an essential part of the local culture, and is used not only for tea and cooking but also to preserve food items by smoking them, repelling mosquitoes and to provide light. Notably in AP, the use of clean cooking fuels is not widely spread, mainly due to the underdeveloped transport infrastructure.

Figure 3.8 shows the percentage of all surveyed households with access to various energy sources. The AP and UP-wide average expenditure on these sources is also given. It is immediately clear that the monthly expenditure on a grid connection seems very low compared to microgrid-based electricity. This, however, is an artifact of most PE households neglecting the payment of the fee. In AP, households pay between ₹ 120-180 for the grid, and in UP all except one household were reported to ignore their electricity bill. According to the interviewees, the reliability of the provided power was so bad that they did not consider it worth paying for. The only household paying for grid connection gave a figure of ₹ 100 as the price per month. For comparison, the microgrid operator Mera Gao Power[5] charges its customers ₹ 120 a month for electricity.

The average monthly amount spent on consumptive energy services was ₹ 155 across all surveyed households. In AP, households tend to pay more, resulting in an AP-only average of ₹ 174. Consequently, in UP the average is lower at ₹ 123 per month. Neither the fixed cost for

---

[5] See section 3.2.1 for details about the company.



* : Fixed cost of solar systems and operating cost of generators were not considered.

Figure 3.8: Current energy access situation across all surveyed households in AP and UP. Average monthly expenditure per household on each energy source is also shown.

solar systems nor the operating cost of diesel and petrol generators were considered in these average values. The generator operating cost was neglected mainly to compare consumptive energy expenditure between AP and UP.

Around 98 per cent of the surveyed ME and NE households own electrical appliances even though not all were able to use them due to shortage in power. Figure 3.9 shows access to different types of light bulbs in AP and UP, whereas household access to other appliances is depicted in figure 3.10. All the depicted appliances, lighting and otherwise, represent consumptive usage.

In AP, households typically have more than one type of lighting source and 98 per cent of homes had access to at least one. In UP, 77 per cent of households have access to lighting via electric bulbs, and they effectively only use LED bulbs. This is largely due to microgrid operators such as Mera Gao Power that provide LED's as part of their microgrid solutions.

Despite their remote location, households in AP have more televisions, with 41 per cent of interviewees owning at least one. The corresponding figure for UP is a mere 6 per cent. Owning a TV set, however, does not directly imply higher consumption rates as many households complained that they do not receive enough power to use their televisions as often as they would like[6]. Even though the monthly cost for satellite reception is relatively high at ₹ 370, households were keen on increasing their television usage.

Fewer people in AP had access to mobile phones than in UP, which may be due to the remoteness of the surveyed communities in AP and the resulting bad or non-existing mobile signal. Here, mobile-phone access was assumed equal to owning a mobile charger. In general, ME and NE households in AP were shown to have improved access to a variety of appliances compared to those in UP. The higher income in the former thus seems to dominate over remoteness and transport infrastructure. Other factors affecting appliance usage in AP and UP

---

[6] 50 per cent of all TV owners in ME and NE households reported they never use it.

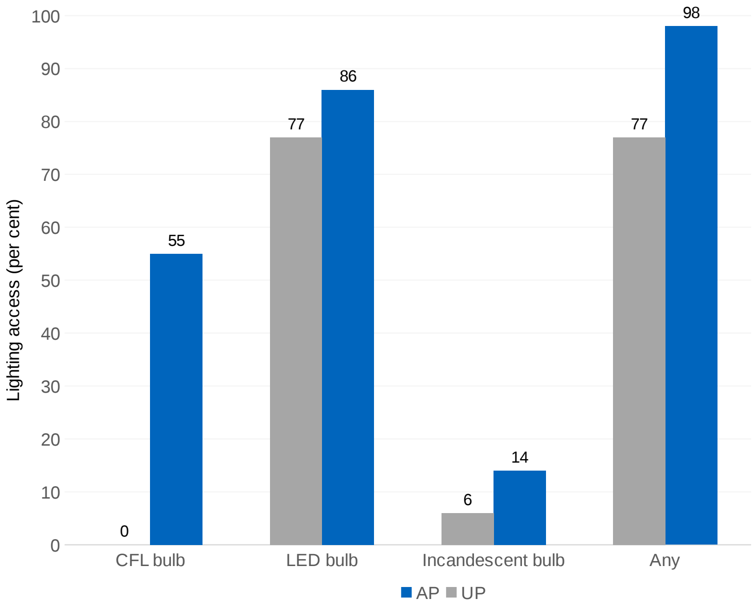


Figure 3.9: The variation in access to lighting in ME and NE households across AP and UP.

include differences in climate; The fact that fans are more widely found in UP is naturally due to higher temperatures and increased cooling need.
It must also be mentioned that the Government of India reached out to many of the surveyed villages in AP in the early 1990's, drawing lines to connect them to the national grid, and giving them incandescent lights. However, according to the interviewees, they never actually received electricity. At present, the lines have fallen into decay, having never been used. Consequently, even though some households in AP own incandescent lights, none actually uses them as they are connected to the old non-functional lines.

Household electricity consumption was determined based on user evaluation of daily usage duration for all electrical appliances. The variation in average monthly consumption in AP and UP is presented in figure 3.11. The monthly electricity consumption was found to be 2.73 times greater in Arunachal compared with UP. This clearly reflects the higher socio-economic status of the households in AP, and correlates with their improved access to electrical appliances. Also, some appliances used in UP, such as fans, are highly seasonal and only used in the hottest or driest months of the year. This further decreases the energy requirement even though the peak power need in UP might be higher.
The electrical energy consumption averaged over all visited NE and ME communities is a mere 2.48 kWh per month per household. This is almost 21 times less than the consumption in the surveyed FE households, and extremely low compared to Western countries. As seen from figure 3.12, the largest electrical load consists of the combination of TV and setupbox (set-top unit), closely followed by the combined lighting load of LED's, CFL bulbs and lanterns (torches).

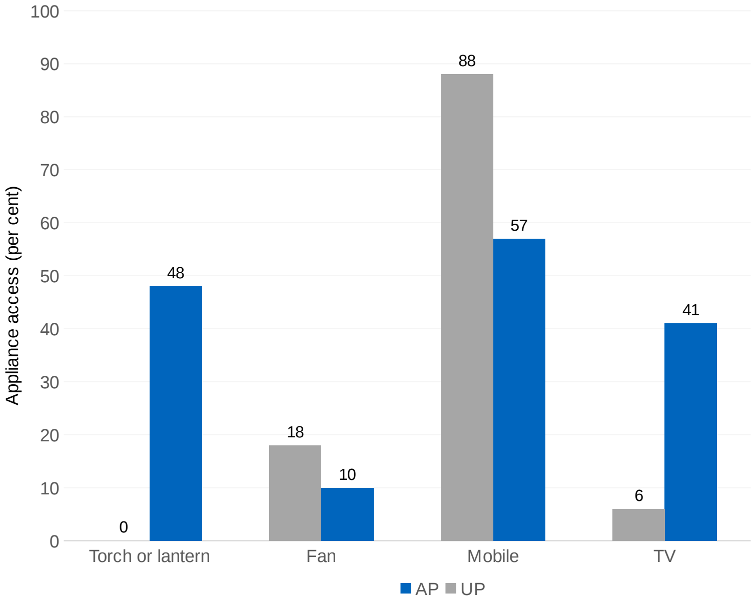


Figure 3.10: Access to common household appliances in AP and UP.

Based on the survey results, the majority of electrical appliances used in AP and UP currently fits into the category of consumptive loads as defined in section 3.2.1. Apart from seasonal usage of water pumps in UP, no productive loads were found. Both states were still found to offer potential productive use cases provided enough power is available.

Promising possible productive use cases in Arunachal Pradesh are weaving, carpentry, drying and packaging of cash crops, and street lights. Especially weaving of traditional dresses could be very affordable, and one household in AP reported a monthly income of ₹ 1,500. At the moment, weaving may only be carried out manually, and only during daytime, when most villagers are out on their fields. With lighting, this activity could be extended to evening and the potential income increased.

In AP, houses and furniture are mostly made of bamboo and wood, and with electric power tools carpentry could be made more viable a profession. According to the survey, 11 per cent of households expressed interest in this type of machinery. Further, most of AP's cash crops are currently dried naturally, which in the humid climate is very slow and may lead to rotting. If enough power was available, this could be done by means of electricity.

In Uttar Pradesh, irrigation pumps are the most obvious productive use case, and the only one villagers are actively spending money on at present. All farmers require irrigation during the dry season, and spend ₹ 2,870 per month, on average, on diesel or petrol to operate the pumps. Twelve per cent of surveyed households own their own water pump and the rest are paying to use one. Provided reliable electricity access, electrical pumps would be a far more economical solution. These could be grid-powered or solar-based.

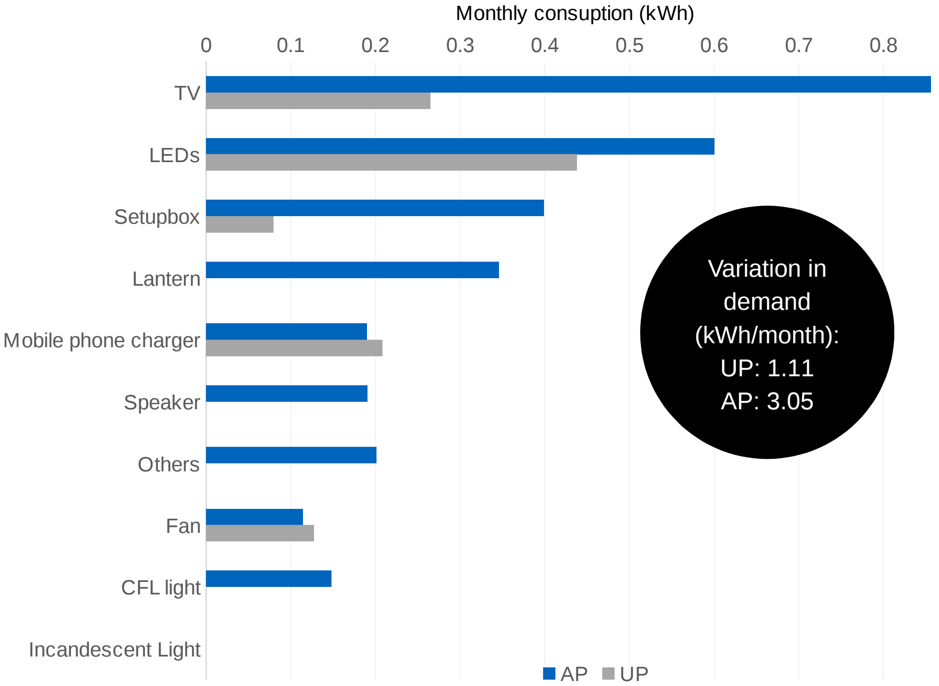


Figure 3.11: The average monthly household consumption by appliance in AP and UP. The averages are based on households that have access to the specific appliances.

Due to the larger size of villages in UP, shopkeeping is also a profitable activity. With lighting, shops could stay open for longer without compromising the security of customers.

In addition to the household and focused-group questionnaires, one specifically targeted at schools was also developed and carried out as part of this study. A governmental residential school was surveyed, situated in the village of Jamupani in Arunachal Pradesh.

The surveyed governmental residential school in Jamupani teaches from year one to year eight, and around 50 children from Jamupani and neighbouring villages stay there nine months a year, along with 10 staff members. Most children in the region attend the school, in part thanks to the government of AP offering two free meals per day, which is a substantial help for many households. Also, the fact that tuition is free of charge is a major contributing factor.

At the time of the energy needs survey, the only source of electricity at Jamupani school were small, privately acquired photovoltaic panels that power eight 3-watt LED bulbs for about four hours per day. These are located in the dorms of staff and pupils as well as the kitchen. Solar lanterns and torches are used to move outside after dark. According to the headmaster, ₹ 1,320 per month are spent on batteries for the torches.

Cooking is done with firewood that the pupils gather in the nearby forest. The lack of electricity is a major problem for security as children have to navigate to outside toilets after dark, and also for the educational aspect as studying becomes impossible after sundown. At the time of the survey, the school was unable to fulfill some requirements of the national curriculum as

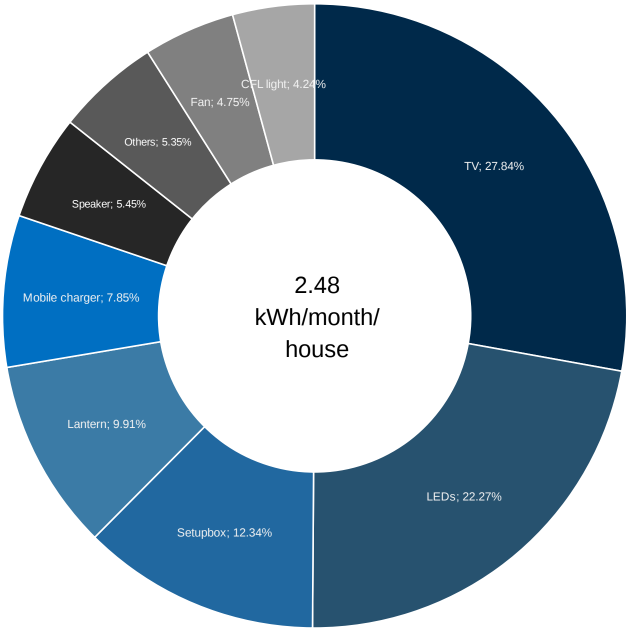


Figure 3.12: Average consumption across all NE and ME households in the survey.

they did not have TV sets[7].

Almost every surveyed ME/NE household in AP and UP showed interest in buying more appliances or increasing the usage of old ones provided enough power would be available. 85 percent of households wished to either acquire a TV set or watch it more often, putting it at the top of their wishlist as shown in figure 3.13. Also, the headmaster of Jamupani school in Arunachal reported hoping for more appliances.

The survey data shows that ME and NE households spend more money (₹ 155 per month) on electricity than FE villages (₹ 130 per month). This is surprising due to the limited electricity access in ME and NE communities. For an electrical load 21 times smaller than that of FE households, ME and NE homes spend 19 per cent more on electricity. Fully electrified households pay a monthly connection fee whereas non-electrified and microgrid electrified homes need to buy batteries, candles, kerosene and petrol.

When asked, those households in AP willing to pay for extra electricity were ready to give an average of ₹ 179 per month. In UP, this figure was even higher at ₹ 193, regardless of their lower monthly income. This is very probably due to the fact that UP households already have a productive use case (water pumping) in place, and know that more reliable electricity is directly related to higher income. In Arunachal Pradesh, the villagers tend to regard electricity purely as an added comfort in the home.

---

[7] According to the curriculum, all pupils must watch certain educational programmes at least once a year. Currently, the pupils of Jamupani school visit one of the neighbouring houses with a television to see the programme.

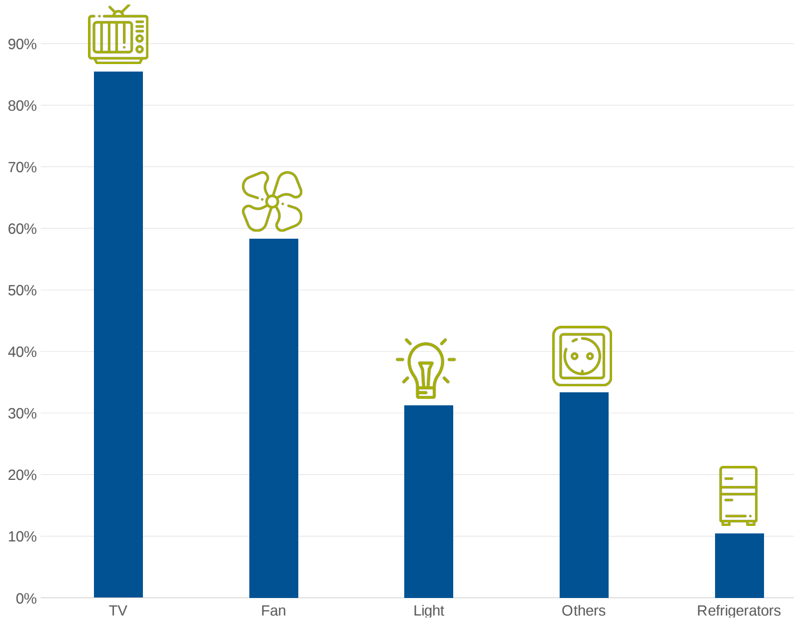


Figure 3.13: Percentage of ME and NE households wishing to buy an appliance or to extend its usage. Smartart from [42].

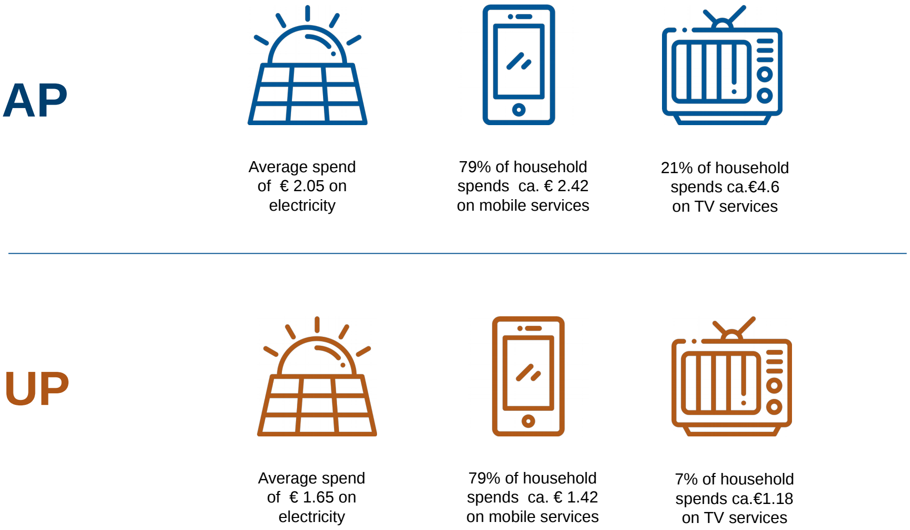


Figure 3.14: Comparison of average monthly expenditure on basic services in AP and UP. Smartart from [42].

3.3 Summary

The surveys conducted in Nepal and India clearly show that the energy demand of rural communities is growing, and that the current electricity supply is lagging behind this development. When in Nepal the interviewed communities found that they cannot buy appliances such as rice cookers because of the dire power shortage, Indian families lamented they cannot switch on their TV sets due to the same reason.

In both countries the main issue hindering social growth is insufficient power supply. Especially the example of Arunachal Pradesh shows that the government has had very little interest in sustaining electricity services in rural areas. The experiences in Nepal, on the other hand, indicate that a faulty business model can also discourage households from saving energy, thus causing harm to the whole community. This was manifested by the fixed monthly fee for a shared amount of power, meaning that those with more appliances consumed more energy for no added cost, at the same time taking resources from their neighbours.

Rural communities acknowledge the importance of electricity and desire to have more of it. The above mentioned studies showed a solid willingness to pay in both Nepal and India, although as seen in Uttar Pradesh, low power quality effectively dissuades households from paying their monthly fees. This is understandable as the families feel they are not receiving any value for money, and choose to use money for other things instead. On the flip side, governments may be less interested in improving the power quality of existing connections as long as people are not paying their share.

The results of the India study in particular were also used to select a suitable location for the sustainable energy system pilot that was to be installed as part of this thesis. As detailed above, the village of Jamupani in the sate of Arunachal Pradesh, India, was found to be home to a governmental residential school of over 50 pupils from the region. Further, Jamupani has abundant solar resources and a non-seasonal stream flowing through the village. Similarly to other villages in Arunachal Pradesh, the locals were willing and able to pay for energy services, and had previous experience of renewable energy in the form of solar lanterns and small-scale PV panels. All these characteristics made Jamupani an ideal location to build a sustainble microgrid. Thus, Jamupani was selected as the target location for the pilot system, and a detailed report of how this system was designed and installed is given in part III of this thesis.

Chapter 4

Analysis of factors impeding access to energy

Two separate studies were conducted to find impeding factors for the advancement of clean and renewable energies in rural areas of the world. India, being the general focus of this thesis, was studied in the context of clean cooking. The use of electricity for cooking is currently not practiced, and most Indian households use firewood (49.0%) or LPG (28.5%) [43]. Traditional fuels are known to cause an environmental burden as well as health issues [4]. Switching to cleaner fuels such as biogas, and to more efficient cooking stoves, could reduce both risks, and India has subsidised numerous projects to that effect [44]. Further, there is a clear connection between renewable energy and clean cooking, as access to clean energy sources can reduce the environmental impact of preparing food. Using electric appliances or biogas also decreases health risks as direct emissions are cut down. In view of the relationship between renewable energy and clean cooking, it was important to study the factors affecting both.

The second study realised on the subject of energy access and the barriers to its advancement was carried out in the rural non-electrified areas of Colombia. Here the focus was on finding reasons to the slow advancement of renewable energy. Both studies were conducted in the form of literature reviews, and several semi-structured interviews of experts and stakeholder in their respective fields, and in the case of Colombia, several site inspections of existing off-grid installations were carried out as well. The work presented in this chapter is based on the Master's theses of Nicolás Mora-Guarda and Lisa-Marie Mildner.

4.1 Factors affecting clean cooking in India

The purpose of the project was twofold. Firstly, it served to study the theory of adoption of innovations. This would aid in introducing renewable energy as a new technology in rural areas. The second aim of the project was the understanding of factors affecting the adoption of a specific technology, namely clean cooking, in India, and thus to obtain a broader perspective on what impediments for renewable energy projects exist in general. The strong link between traditional cooking fuels, efficiency of cooking stoves and overall energy need was the main motivation to carry out this research. The interviews were conducted in October 2018.

4.1.1 Method

First, a thorough literature review was done to study the process of adoption of new technologies, and to apply a suitable framework to the case of clean cooking. The review was also necessary to find out which fuels and cooking methods are currently in use in India. Further, the role of public, private and third (NGO) sectors in the clean cooking field was examined, and various behavioural models for the transition from traditional fuels to clean cooking were reviewed. This step produced an initial set of influencing factors that were used as comparison for the expert interview results.

To obtain a better understanding of the current reasons for lacking adoption of clean cooking technologies in Indian households, experts from the private and third sectors were interviewed. As the obstacles for the advancement of clean technologies are manifold and cross-disciplinary, a qualitative rather than quantitative approach was deemed more fruitful. Semi-structured interviews were chosen to make it easier to speak to interviewees of diverse cultural and educational background, while still maintaining the ability to compare the results [45]. A rough question guide was prepared prior to the interviews, detailing direct questions and possible follow-up questions. The guide was meant to give context and structure to the interviews without withholding the right to speak freely from the interviewees.

The guide was based on the findings of the earlier literature review, and sought to make clear the separation between short-term and long-term adoption of clean cooking technologies. This was deemed important as, during the literature review, the rates of initial adoption were found to substantially differ for the long-term figure. The prepared guiding questions are shown in table 4.1.

The first guiding question was used to get an idea of the interviewed organisations' activity in clean cooking, whereas the next two questions put more emphasis on the knowledge gathered by the organisations when implementing and monitoring clean cooking projects. This set of questions was intended to lead interviewees to speak based on the obstacles that they had faced when implementing clean cooking strategies.

Table 4.1: Guiding questions for the semi-structured interviews on clean cooking.

Number	Guiding question
`GQ1`	I am especially interested in the activities of your organisation in the clean cooking sector. Can you please describe the activities of your organisation in this field?
`GQ2`	I would like to know more about the project(s) in the field of clean cooking. Can you please describe the introduction of clean cooking technology in the village(s) on-site?
`GQ3`	Can you please describe the usage after the initial introduction of the clean cooking technology?
`GQ4`	In your opinion, why do households not adopt clean cooking technologies?

The sampling of the semi-structured interviews was carried out using a technique know as generic purposive sampling. Following this technique, respondents are selected based on generic criteria that are set prior to the interview process. In this study the criteria were set based on the initial literature review as follows:

- Experience in clean cooking technologies. Sometimes it is good to explore other innovations that have a similar impact on their respective markets, but this study restricted itself to the target technologies only.
- Organisations working in the private or third sector. Based on the literature review, companies and NGOs seemed to have a better understanding of end-user demand patterns than the public sector[46]. This is due to the former usually being directly involved in the implementation of clean cooking technologies on site.
- Individuals with hands-on experience of implementation. It was deemed important that the individuals interviewed from each selected organisation had personal on-site experience in order for them to deliver first-hand information.

In total, four extensive interviews were conducted, comprising one for-profit enterprise, a social business, an NGO, and a research institute. The for-profit organisation sells improved cooking stoves and wood-based fuel pellets that reduce indoor air pollution. Their business model is based on a cross-subsidisation scheme, and their revenue comes from commercial customers that pay for the fuel pellets. The villages are given a stove and fuel in exchange for wood gathered by them, and later processed into pellets by the company. At the time of the interview, the company had implemented a pilot project in Bhutan.

The social enterprise has a business model of teaching unemployed villagers to build and sell improved biomass-based cookstoves. The design is simple, affordable, and capable of reducing indoor pollution. However, they had been facing technological and economic problems and were actively searching for other possible clean cooking technologies. Before October 2018, they had implemented a prototype in Uttar Pradesh.

The NGO are involved in many areas ranging from social tourism to sanitation, and their clean cooking experience is based on partnership projects with other organisations. They too had mainly been active in Uttar Pradesh prior to the interview. The interviewed research institution pursues the advancement of clean cooking to improve gender equality and mitigate poverty. At the time of the interview, they were active in a project introducing electric cookers to villages in Rajasthan and Chhattisgarh. Further, the institute is involved in public policy research to promote clean cooking technologies.

To mitigate the small sample size of the semi-structured interview study, care was taken to choose organisations with wide variety of backgrounds and goals. In this manner, a broad overview of experiences and opinions was obtained.

4.1.2 Results

In India, the use of traditional fuels is tightly coupled with health issues. The majority of Indian families use biomass such as firewood and dung cakes for cooking, causing harmful emissions within the households[47]. It is widely accepted that using cleaner fuels or better cooking methods could improve the situation, and numerous public and NGO-backed projects have been established to promote clean cooking technologies[48]. Despite these efforts, however, adoption rates for the cleaner alternatives has been low.

The latest census data for India shows that the main fuel used by households in India was firewood at 49 per cent, followed by LPG at 28.5 per cent. As seen in figure 4.1, the use of

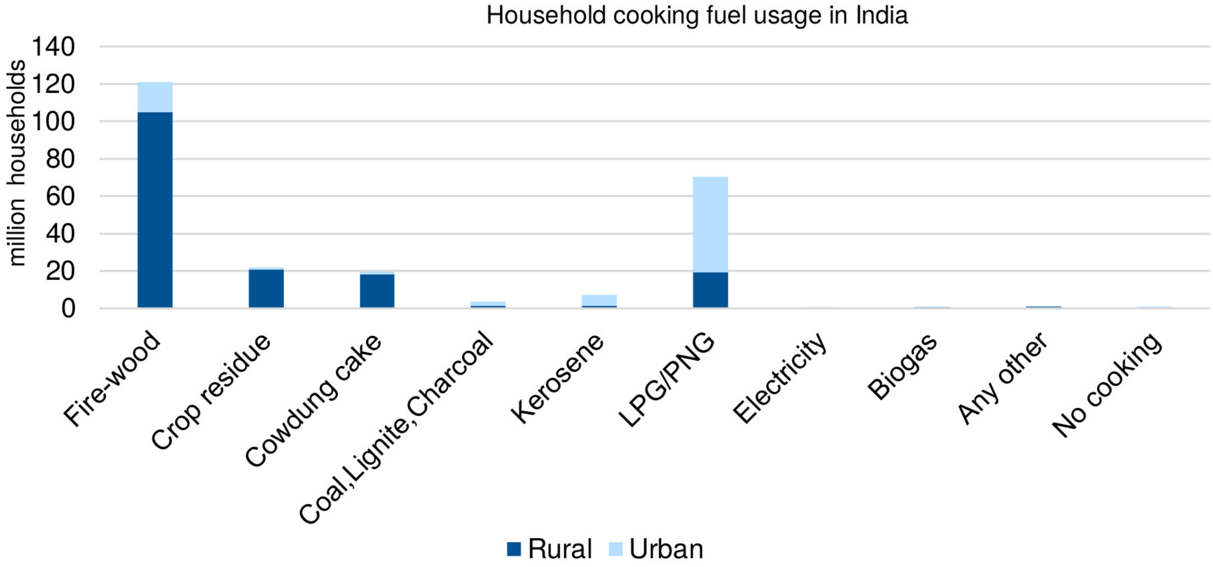


Figure 4.1: Cooking fuel usage in Indian households[49].

electricity or biogas was nonexistent. The same figure shows that the popularity of LPG is focused on urban areas, meaning that most rural households rely on firewood, crop residue and dung cakes. Moreover, most (87.3 per cent) Indians cook indoors, most with no air conditioning to get rid of harmful smoke. Using traditional fuels such as biomass lead to incomplete combustion and particulate emissions[50]. LPG burns more efficiently, thus causing less direct health effects, but produces higher levels of CO_2. These emissions are detrimental both to the environment and human health. The Government of India started promoting clean cooking technologies in the early 1980's, focusing on improved cookstove design and LPG. The latter is heavily subsidised and has significantly increased in popularity in the urban areas. However, rural regions still lag behind, mainly due to complicated logistics and sparse population[1]. In 2016, the government launched a campaign (PMUY) to bridge this gap.

Biogas and electricity are also promoted by the government. Between 2017 and 2018, the Indian government subsidised small biogas plants for rural and semi-urban households. This programme has been continued under the name New National Biogas and Organic Manure Program, and it aims to install at least 255,000 biogas plants[]. The Indian Ministry of New and Renewable Energy promotes using solar energy for cooking, and India has been aiming to connect all households to the electricity grid for years. Still, only 0.1 per cent of households were using electricity for cooking according to the latest census.

The private and third sector have also been active in the area of clean cooking in India. Many private companies have struggled in the market, however, mainly due to the massive LPG subsidies of the government[51]. These subsidies distort the market and push companies from selling to private customers to commercial ones. Many companies have also chosen not to target the lowest income groups, thus leaving those most affected by traditional fuels without support[51]. The third sector, namely NGO's, are currently also promoting clean cooking

---

[1] This information was obtained during the energy need survey conducted in Arunachal Pradesh. See section 3.2.2.

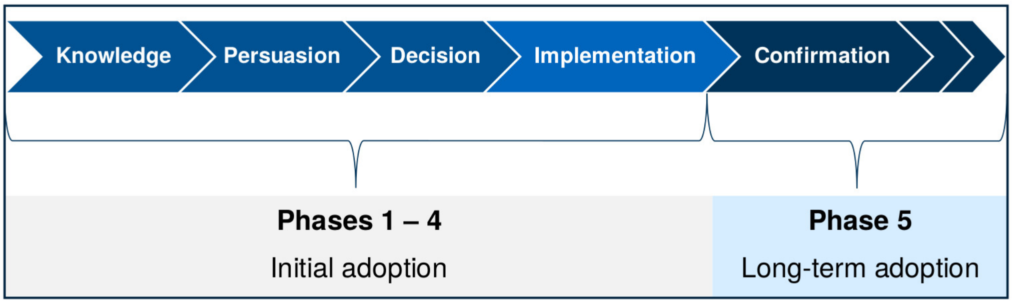


Figure 4.2: The innovation-decision process[54][49].

technologies in India. Reportedly around 240 NGO's are actively working to increase the share of biogas, kerosene LPG, solar technology and electricity[48].

According to literature, one of the main barriers to adopting new technologies is cost[52]. But based on the experiences in India, it would be wrong to suggest that increasing income or access to more affordable technologies would automatically lead to increased adoption. This can be seen in the heavy subsidies of LPG and its low adoption rate in rural areas. Clearly, fuel switching is not only a question of affordability. For example, traditional cookstoves are an integral part of Indian culture, and interwoven into the lifestyle of many Indians[53].

To better understand the adoption of clean cooking technologies, an innovation-decision process model was used to analyse the information obtained from the literature and the interviews. Figure 4.2 details how this process works. The different phases of the adoption process are explained in table 4.2 Applying the innovation-decision model to clean cooking technologies, critical factors affecting their adoption were identified. Especially in rural areas, many households are not aware of the existence of clean cooking, which stops the adoption process at its first step[55]. Also, villagers' knowledge about the health hazards and environmental impact of traditional fuels is low. Further, many households find that the benefits of clean cooking do not outweigh those of traditional fuels. Biogas stoves are widely used for lighting and to repel insects as well, which most clean cooking technologies do not do[56]. To form a positive opinion of a technology at the persuasion phase, cultural loss and the potential loss of convenience must be overcome by the perceived benefits.

As mentioned before, one of the main barriers in the decision phase is not being able to test the clean cooking technology as free trials are hard to organise. Household income is also a major factor at this phase, because even if the family are interested and willing to take on a system, they might not have sufficient funds to buy or maintain it, leading to a decision not to adopt. This problem may be mitigated with subsidies if they are correctly allocated. For instance, the subsidies given for LPG were found to mainly benefit wealthier households, never reaching those needing them the most[57].

Factors affecting the adoption at the implementation phase include unskilled and faulty installation due to lacking experience or time, and using a top-down approach without taking into account local circumstances. These might include placing a biogas plant somewhere where it will not be damaged during monsoon, or using solar-based solution only in regions with enough irradiation. Even more evidently, as women are usually responsible for cooking, the training to use cooking devices should be predominantly aimed at women, not men.

Table 4.2: Phases of the innovation-decision process model adapted to clean cooking technologies[54].

Phase	Description
`1. Knowledge`	Exposure to knowledge about clean cooking technologies. The potential user learns about their existence, how they work and what benefits they offer. The user's interest in the technologies must be sparked in order for the adoption process to continue. Lack of knowledge at this stage is a clear barrier to adoption.
`2. Persuasion`	The potential user creates an opinion about the technology. They search for additional information such as how it is perceived by others in the community, how it fits in their cultural context etc. People that have already adopted clean cooking technologies are in a key role to propagate adoption. A general negative opinion, or that of someone of higher authority, may become an obstacle to adoption at this stage.
`3. Decision`	The potential user decides whether to adopt the new technology or not. This decision is still not final as the user might reject the new technology after testing it. If testing is difficult (bad logistics, unwillingness of seller to offer trial periods), adoption is hindered.
`4. Implementation`	The chosen clean cooking technology is taken into operation. The user now needs to have the necessary information to operate and maintain the technology. Malpractice or abuse of the technology may give unwanted results and dissuade users from continuing the adoption process.
`5. Confirmation`	The long-term adoption of the chosen clean cooking technology depends on the satisfaction of the user. If the technology does not perform as promised, or does not meet the expectations of the user, its use will be discontinued. Technical failures or mishandling due to lack of knowledge might cause the technology to be abandoned. Also, lacking financial means may cause users to abandon a technology. Innovations may also be replaced by new ones with time, which is a positive form of adoption discontinuance.

Similarly to the decision step, the successful long-term adoption (confirmation phase) of clean cooking technologies is strongly influenced by household income. If any running costs exist, limited financial resources may force families to give up the technology even if they find it beneficial. Also, insufficient knowledge about the system gathered throughout the adoption process may lead to discontinuation. Knowing how to correctly use and maintain a system is key for its long-term adoption[58]. Other reasons for lacking long-term adoption include bad infrastructure, as seen in the case of LPG in rural areas, too high expectations of the benefits, and low perceived value of the new technology. The latter may occur in cases where a clean cooking technology is given to users for free, and they fail to appreciate its real value.

The results found during the literature review were used as basis for the semi-structured interviews introduced in section 4.1.1. Many of the same factors came up in the discussions, and the interviews served to judge the relative importance of each factor.

The government subsidies were generally found to catastrophically affect the advancement of clean cooking technologies. LPG, sanitation and electricity are heavily subsidised where infrastructure allows, effectively making it impossible for private suppliers to compete on the market. This is a problem because the subsidies only cover the initial installation, not the subsequent usage and maintenance. Thus the long-term adoption does not take place and the households grow more wary of similar technologies. At the same time, potential users' willingness to pay is low and companies have to push their prices to unsustainably low levels.

Lacking awareness of health and environmental issues caused by traditional cookstoves were widely seen as an issue. According to the interviewees, people in India are aware of the immediate problems such as coughing, sore throat etc., but have little knowledge of long-term effects like cancer and lung malfunction. Further, the respondents claimed that no nation-wide awareness campaigns about clean cooking have been put in place. Due to this, even though most people are aware of the LPG scheme, they do not know the reasons behind it. Some reject cleaner technologies out of mistrust because they do not understand fire without smoke.

The interviewees also reported lacking R&D to be an issue in the adoption of clean cooking technologies. New technologies often fail to take into account culture, habits, and cooking needs. The used materials might not be resistant enough, or the new stove might not fit the pots and pans used in the household.

Gaining trust is not easy, and most interviewees emphasised the need to convince village heads of the new cooking technology before approaching the villagers themselves. The difficulty of giving out trials was mostly circumvented by organising public cooking demonstrations before distributing new stoves.

The low status of women in the society was widely seen as one of the key factors impeding the advancement of clean cooking technologies. Even in families with enough funds, men often spend the extra money on status symbols like smartphones or TV sets, rather than on improving the cooking conditions of their wives and daughters. Some interviewees emphasised that if the men do not care about the health of their wives, no amount of information about the benefits of a system will make them adopt it.

Lack of infrastructure was generally agreed to be a significant obstacle. Electricity-based solutions are infeasible in areas where the grid connection is unreliable, and impossible in the most rural regions. It was again brought up that LPG was not successful in rural India because of insufficient transport infrastructure. Maintenance was also seen as key to successful adoption, which is considerably harder in non-urban areas.

Table 4.3: Influencing factors in the adoption of clean cooking technologies.

Initial adoption				Long-term adoption
Knowledge	Persuasion	Description	Implementation	Confirmation
Awareness lack of knowledge of technologies and benefits negatively affect initial adoption	**Information source** absence of credible sources such as peers of NGO’s	**Trial** missing possibility for trials can dissuade potential users	**Training & assistance** insufficient training leads to suboptimal operation	**Running costs** high costs may lead to discontinuance
User needs & relevance neglecting user needs leads to an uninteresting product	**Characteristics** high complexity, cultural incompatibility and insufficient benefits lead to negative opinion	**Investment cost** High cost of investment may lead to rejection	**Local circumstances** Not taking care of local circumstances (weather, location etc.) could result in suboptimal performance	**Infrastructure** Lack of infrastructure can hinder long-term adoption
		Households decision structure Not convincing the right person may lead to a negative decision		**Handling and maintenance** mishandlings or neglected maintenance may result in failures
				Performance unmet expectations cause dissatisfaction
Gender issues the lower status of women may influence all steps of the adoption model				
Education lack of education hinders understanding and negatively influences the whole adoption process				

Finally, behavioural change was brought up as an issue. It was seen as difficult to change the habits of people who have been cooking with traditional fuels for years. Especially older villagers have trouble adopting new technologies, and as they are usually respected by the younger generations, this may stall the adoption process in a whole community.

All factors identified during the literature review were addressed by the respondent of the interviews. Financial factors were seen as very impactful, as were gender equality and respect for tradition. A summary of the key factors influencing adoption of clean cooking technologies are shown in table 4.3.

4.2 Barriers to renewable energy systems in the Colombian context

The aim of the research conducted in Colombia was to determine factors for the lacking adoption rate of renewable energy systems in the non-grid-connected areas of Colombia. These off-grid areas[2] account for over 50 per cent of Colombia's national territory, and despite high potential for diverse renewable sources, these regions obtain 96 per cent of their power from diesel. This discrepancy between supply and demand pointed at possible socio-economic factors being at play as opposed to technical ones.

As in the India study, this research comprised a thorough literature review and several semi-structured interviews with experts on rural electrification in Colombia. Additionally, three on-site inspections were conducted to different regions of the non-interconnected zones. The study was carried out between July and September of 2019.

4.2.1 Method

As per the literature survey, the adoption of renewable off-grid systems faces diverse barriers from technical to economic and cultural. Fourteen different stakeholders and organisations active in the field of renewable energy were identified, along with 11 possible factors affecting its adoption. Based on these findings, a set of three guiding questions was designed to help structure the interviews. The questions are shown in table 4.4.

---

[2] The areas are collectively known as non-interconnected zones, or *zonas no interconectadas* in Spanish[59].

Table 4.4: Guiding questions for the semi-structured interviews on renewable energy adoption in Colombia.

Number	Guiding question
`GQ1`	What do you think is the position of the following entities[3] towards the implementation of renewable energy in the non-interconnected zone? 1. Against 2. Indifferent 3. In favour
`GQ2`	From 1 to 5, where 1 is very little and 5 a lot, how influential (positively or negatively) do you think the following entities are for the adoption of renewable energy systems in the non-interconnected zones?
`GQ3`	Regarding the illegal groups operating in Colombia, namely guerrillas (ELN, FARC dissidences, etc.), paramilitaries, drug trafficking and illegal mining, please choose the option that most represents your opinion: 1. These groups / activities negatively affect the implementation of renewable energy systems in the non-interconnected zones. 2. These groups / activities do not affect the implementation of renewable energy systems in the non-interconnected zones. 3. These groups / activities positively affect the implementation of renewable energy systems in the non-interconnected zones.

A short description of each identified stakeholder is given below:

1. The ministry of mines and energy (MME)

   Public entity. The main institution in charge of Colombia's power sector with significant power in terms of policy and legal framework concerning energy and network expansion.

2. The national planning department (DNP)

   Public entity. Prepares, oversees and evaluates the execution of public policies for economic, social and environmental development. Partially responsible for funds granted to electrification projects in the non-interconnected zones.

3. Mines and energy planning unit (UPME)

---

[3] The entities mentioned in the guiding questions refer to the 14 identified stakeholders.

Public entity. Special administrative unit of MME. In charge of creating the national energy plan for electricity generation and transmission expansion. Responsible for energy planning in the non-interconnected zones.

4. Institute for planning and promotion of energy solutions for non-connected areas (IPSE)

   Public entity. Implements, oversees and evaluates renewable energy projects in the non-interconnected zones.

5. The energy and gas regulation commission (CREG)

   Public entity. Sub-unit of MME regulating gas and electricity activities in Colombia. Responsible for creating energy tariffs.

6. Superintendent of public and home services (SSPD)

   Public entity. Responsible for the protection of user and energy provider rights and duties. Evaluates the quality of electricity services in the non-interconnected zones.

7. The collegiate body for administration and decision (OCAD)

   Public entity. Assesses and approves projects to be funded by the General Royalties System.

8. Territorial entities

   Public entities. Autonomous units that manage their own interests in terms of policies and taxes, only limited by the Colombian constitution. Departments, districts and municipalities.

9. Electricity service providers in the non-interconnected zones (ESP)

   Private entities. At the time of writing, 76 electricity services providers were registered under localities properly coded by state agencies. Out of these, only 12 complied with the financial reporting obligations set by the SSPD. 82 per cent of the revenues reported by the companies were subsidies for low-income end-users, and 12 per cent direct payments from clients. Table 4.5 shows how the companies can be divided into categories based on their corporate structure.

10. International development organisations

    Foreign public and private entities. The organisations working in Colombia include USAID, GIZ, United Nations Development Program, and many others. They are active in numerous fields, and not necessarily focused on rural electrification alone.

11. Universities and research centres

    Public entities. Many Colombian universities study the energy access situation in the non-interconnected zones, and have carried out small-scale projects in rural communities. Their direct impact on policy or user habits is not very significant.

12. Illegal groups

    Private entities. Colombia has a long history of armed conflicts between the government and guerrillas. Drug trafficking and illegal mining is frequent, and these groups have a lot of power in rural communities. They are dependent on government-subsidised diesel to operate, and see the introduction of other energy sources on the market as a threat. They can negatively affect the advancement of renewable energies in the non-interconnected zones.

13. End-users

    private entities. The end-user make the final decision of adopting or not adopting new technologies. Without their acceptance, advancing renewable energy in the interconnected zones has little benefit.

14. Communities

    Private entities. Communities can persuade individuals to adopt innovations, and have the responsibility of educating and supporting these individuals in the use of new technologies implemented within the community.

Table 4.5: Electricity services providers in the non-interconnected zones by corporate structure.

Quantity	Corporate structure
36	ESP - Society
26	Authorised organisation: administrators, service co-operatives, work associative companies and user associations
9	Municipality - direct provision
4	State-owned industrial and commercial company
1	Special provider

Thirty semi-structured interviews were conducted to assess the factors hindering the adoption of renewable energy technologies in Colombia. The interviews were given structure by the guiding questions defined previously, and the results were compared to the findings of the initial literature review. The sampling of the respondents was based on two criteria:

- Extensive experience in renewable energy systems in the non-interconnected zones of Colombia
- Alternatively, experience in the Colombian armed conflict.

The background of the interviewees was very varied, and their interest in the renewable-energy sector equally so. Nevertheless, the broad consensus was that clean technologies should be promoted. The respondents could be roughly categorised into the following four groups:

- Academics - seven interviewees
- Energy generation companies - eight interviewees
- International development agencies - seven interviewees
- Official authorities - eight interviewees

The third and final phase of the Colombia study consisted of field research in three distinct departments of Colombia: Amazonas in the Amazonia (South), El Chocó in the Pacífico (West), and Guainía in the Orinoquía (East). The municipalities visited in each department are listed in table 4.6, and shown on the map in figure 4.3.

All three regions are part of the non-interconnected zones of Colombia, but vary substantially in culture, location and state of development. All of these regions have their own unique

Table 4.6: Villages visited as part of the Colombia study.

Department	Villages	Renewable off-grid systems
`Amazonas, Amazonía`	20 de Julio, San Martín de Mayaco	2 nonoperative solar parks
`El Chocó, Pacífico`	Quibdo, Unguía, Bellavista, Vigia del Fuerte, Riosucio	no installations
`Guainía, Orinoquía`	Inírida	one operative solar park

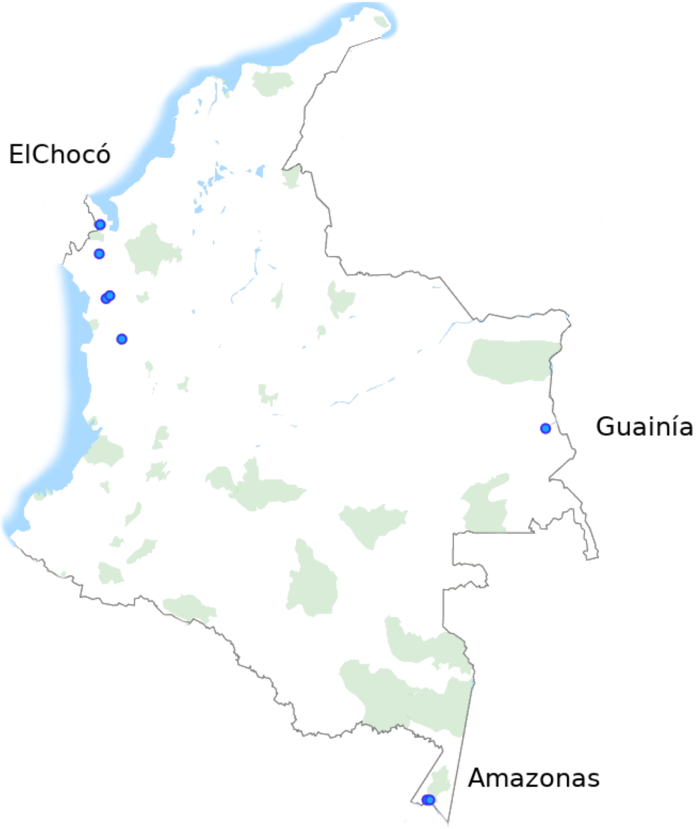


Figure 4.3: Map of locations visited as part of the Colombia field research[26].

sets of problems regarding the dissemination of renewable energy technologies. Specifically, Amazonas is home to three large-scale solar parks, built between 2016-2017, that have since fallen into oblivion without ever having been deployed. El Chocó, on the other hand, is strongly influenced by problems of social order, such as corruption and trafficking, which at present make integrating renewable energy into the area all but impossible. In Guainía, a solar power plant has recently been taken into use and is considered a success story in the region. The three locations of field research were subsequently used as case studies, and were assessed utilising the factors affecting the adoption of renewable technologies that were identified in the literature review and interview processes prior to the on-site visits. Each factor or barrier was analysed in the local context, and given an impact rating (low, medium or high), depending on how meaningful it was in the studied region.

4.2.2 Results

The Colombia study concentrated on the factors affecting access to renewable energy directly. In the past 30 years, Latin America and the Caribbean have seen a significant improvement in electricity access, increasing from 89 per cent to 98 per cent[60]. In Colombia specifically, 1.4 million people still lack access to electricity, out of which 93 per cent live in the non-interconnected zones[61] or ZNI[4]. These areas are characterised by sparse population and difficult terrain. The transport infrastructure is weak and the population mainly poor. Due to these challenges, grid extension has not yet taken place.

The main source of power in the ZNI are diesel generators, but the service is often unreliable and expensive. Although Colombia has abundant solar and hydro power resources, the use of renewable energy has not widely caught on. According to the literature, the main barriers impeding the advancement of renewable energies in rural communities are not technical, but rather social and economic[12]. There is a wide consensus that off-grid renewable energy systems are technically feasible in the vast majority of cases, and that non-technical issues prevent them from succeeding.

As per the literature survey, there are a myriad of technical, economic, institutional, social and environmental issues hindering the adoption of renewable energy systems across the developing world. These barriers have been found to vary from region to region[12], suggesting that there is no one-fits-all solution, not even within one country. For Colombia and the ZNI specifically, insufficient infrastructure for energy distribution and high capital cost of renewable projects were found to be significant barriers[62]. Bad infrastructure generally increases the cost of implementation, resulting in renewable energy systems that are 50 to 70 per cent more expensive than those implemented in areas with better access. Also, maintenance becomes a problem with lacking road access and long distances as operation and maintenance costs often become too high for poor communities. This leads to discontinuation even after successful initial adoption of renewable energy.

Even in places where the long-term costs are manageable, the high initial investment cost dissuades communities from adopting a technology. But as seen in the previous study regarding clean cooking in India, subsidies from the government only covering the initial implementation of a new technology may not be beneficial as it distorts the market, and reduces people's appreciation of the value of the innovation. In Colombia, however, governmental support in the energy sector is still heavily concentrated on diesel[63], and there is an absence of regulatory frameworks that would support renewable energy. Thus, having an initial subsidy for renewable off-grid installations could potentially improve the share of renewables, and initiate a shift away from diesel.

Lack of interest by politicians, resulting insufficient support, and lack of experience and information about previous renewable-energy projects were also found to be barriers to the advancement of renewable energy in Colombia[64]. At least some of the political disinterest derives from the thriving corruption at local and regional level. Colombia has seen decades of armed conflict and clandestine groups are still active in the country. A vast black market for diesel has developed over the years and is directly linked to guerilla groups and drug cartels. The possibility of armed attacks, the reluctance of local governments to help, and the high

---

[4] Zonas no interconectadas.

subsidies on fossil fuels are effectively smothering investment and entrepreneurial activities in the renewable energy sector.

In the semi-structured interviews conducted as part of the study, the failure to consider cultural aspects in the target community was emphasised as a major barrier for initial adoption as well as long-term success of renewable energy systems. Projects were also criticised for not including long-term feasibility plans and having a drop-and-forget attitude.

In many cases, the communities themselves are not ready for change and reject improved electricity access out of fear that it would drastically change their traditional way of life. The interviewees gave examples of villages where solar systems had been installed despite the objections from the community. After installation, the villagers took apart the systems and either sold the components or used them for something else. These examples go on to show that if the community does not appreciate the new technology or if there is no perceived improvement in using it, it is bound to fail in the long term. As discussed in section 3.2.2 regarding the Survey in Uttar Pradesh and Arunachal Pradesh, a fundamental requirement for off-grid energy systems to succeed is that communities have productive use cases in place.

In the India study on clean cooking technologies, the end user was taken into the centre of attention, and an adoption-based model was used to identify factors affecting the advancement of the technology. The Colombia study, on the other hand, took a broader view and identifies various stakeholders in the non-interconnected areas (see section 4.2.1). These stakeholders were then presented to the responders of the semi-structural interviews, seeking to map their positions and impact in the adoption of renewable technologies. Knowing which stakeholders have the most impact, which fields they are active in, and where their activities overlap is necessary to define strategies and suggestions for sustainable renewable energy projects. From a practical point of view, it is important to identify which stakeholders affect which barriers to advancement of renewable energy systems. This is so due to the simple fact that a single pilot project can realistically only tackle factors that are in the hands of the community, the technical experts and at the very maximum, the local government.

The first of the guiding questions of the semi-structured interviews involved the perceived attitude of the various stakeholders in the ZNI towards renewable energy. The results to this question are shown in figure 4.4. Among the interviewees, there was the unanimous view that universities and international development organisations are actively promoting renewable energy technologies, which is unsurprising. It is more interesting to note that the national planning department (DNP) and the energy and gas regulation commission (CREG) were seen as partially indifferent or even hostile towards sustainable energy sources. This links back to the concern over corruption and slow decision making. In general, however, all but one entity can be described as in favour or indifferent towards renewable energy projects. The stakeholder that stands out are the ZNI electricity service providers. The companies that make their profit through selling and distributing diesel are understandably against cleaner technologies, but the threat of armed attacks by illegal groups involved in the black market for diesel is also a key factor in why many providers oppose renewable energy.

The attitude of local communities and end users towards renewable energy systems was seen as indifferent or positive. This can be interpreted as the villagers' being more interested in having electricity than whether it comes from traditional or renewable sources. The fear of coming into conflict with illegal groups, and the lack of awareness about the environment might

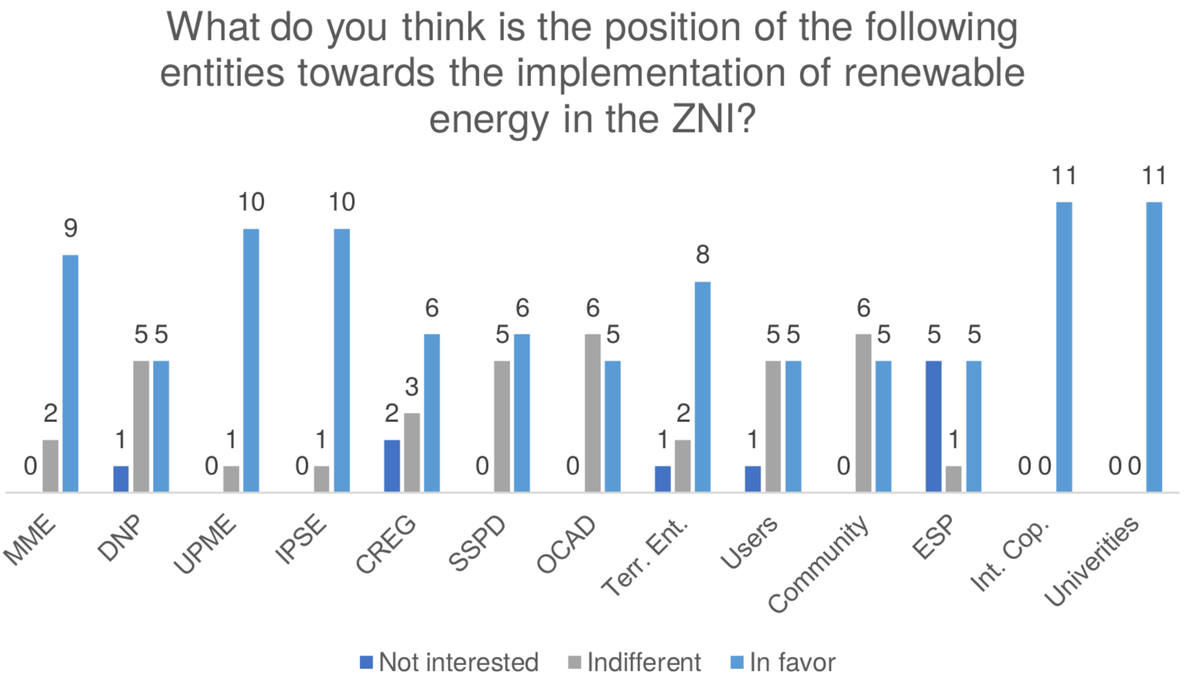


Figure 4.4: Answers to the first guiding question[65].

also affect end users' opinion. The second guiding question in the interview covered the impact of each stakeholder as seen by the interviewees. These results are shown in figure 4.5. Public entities such as MME, IPSE and CREG were considered the most influential stakeholders in the ZNI, but despite their (mainly) positive attitude and perceived impact in the area, little progress has been made to promote renewable energy[66]. This could be due to the lack of efficiency present in these entities, leading to slow decision making and ineffective change. Also, as CREG was deemed partially indifferent and even opposed to renewable energies, their actions might be pushing against other influential entities. Further, many public entities have overlapping activities which may further slow down change due to conflicting policies and lacking transparency. Table 4.7 shows the overlapping functions of many stakeholders in the ZNI.

The ZNI electricity service providers were also considered influential. Due to their split opinion on renewable energy systems, and knowing that currently almost 100 per cent of electricity is generated with diesel, it is clear that this entity is hindering the advancement of sustainable technologies in the ZNI. Many of the leading providers are established enterprises with vast market shares in the area, effectively barring new electricity providers from entering the market. Here, political change is needed to make market entry easier for starting renewable energy providers.

The last guiding question was about the illegal groups operating in Colombia, and their impact on the dissemination of renewable enrgy technologies. This question was difficult to answer by the interviewees and they expressed fears for their own safety if they acknowledged the issue publicly. The negative effect of the black market diesel was acknowledged universally, but no official evidence exists due to the threat of armed attacks against those who speak out. Clearly,

Table 4.7: Overlap of the functions of the stakeholders in the ZNI[66].

Function	Entity								
	MME	DNP	UPME	IPSE	CREG	SSPD	OCAD	Terr. entity	Community
`Political definition`	x	x							
`Planning`	x	x	x	x					
`Project structuring`		x		x				x	x
`Project evaluation`		x	x	x				x	
`Grant approval`	x	x	x				x	x	
`Project contracting`	x			x				x	
`Supervision & inventory`	x	x		x				x	
`Technical regulation`	x								
`Economic regulation`	x	x			x				
`Inspection, monitoring & control`						x			

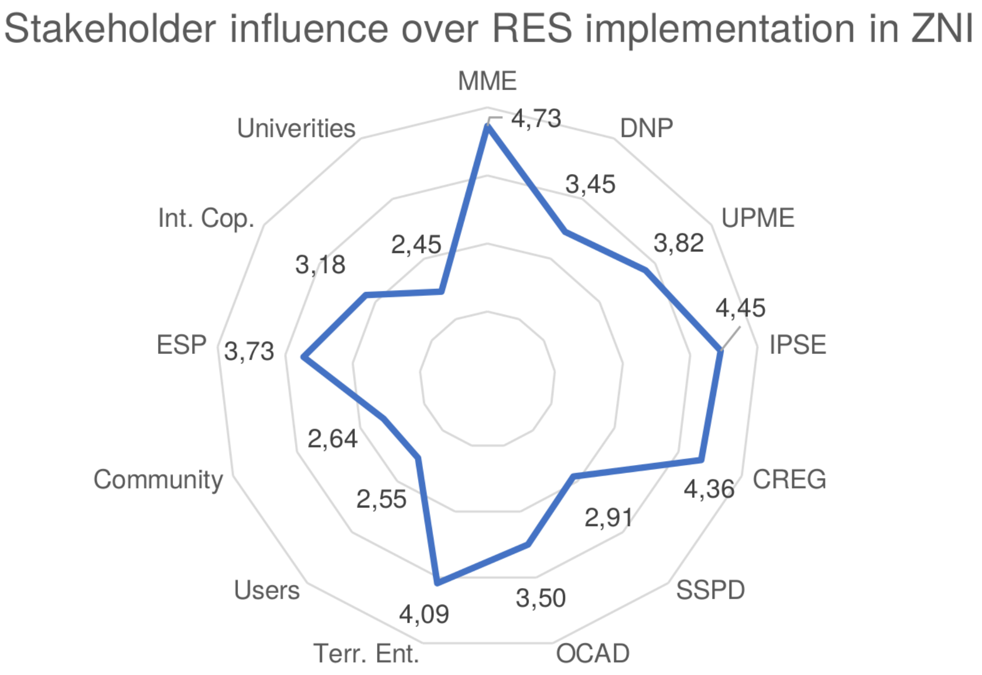


Figure 4.5: Answers to the second guiding question[65].

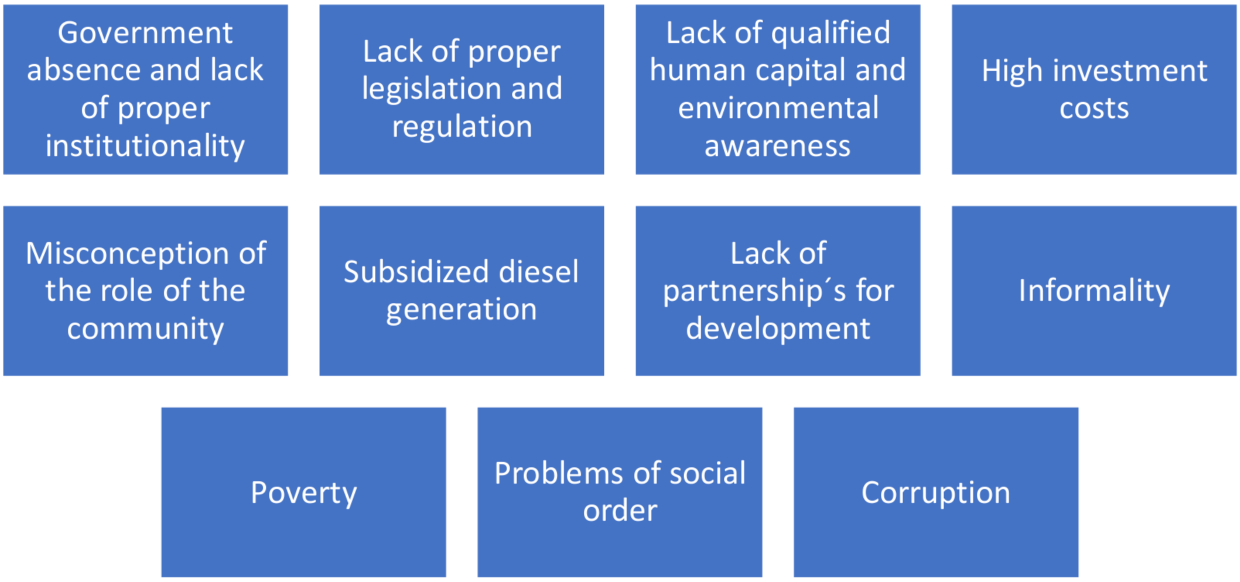


Figure 4.6: The 11 non-technical barriers hindering the advancement of renewable energy in the ZNI[65].

illegal groups are an issue that cannot be fought on a local or communal level.
Finally, after the initial literature review and the extensive interviews, a total of eleven barriers to renewable energy systems in the ZNI were identified. As seen throughout the study, technical issues were found to be of far lesser significance than those of social, economic and legal origin. Hence it is unsurprising that all of the eleven factors are non-technical in nature. These factors are presented in figure 4.6, and described in detail below. The factors are not presented in any particular order.

1. National government absence and lack of proper institutionality
   - The rural regions of Colombia have historically received very little interest from the government. Support for rural development has always been lacking, especially in the ZNI. This is made evident by figure 4.7 which shows that the five poorest departments in Colombia are all part of the ZNI. The lack if support in the ZNI leads to lack of guidance and information, and periodical discontinuity of projects whenever a change in government occurs. Further, the non-existent institutionality of local organisations involved in the electrification of the ZNI makes it hard to create standards and solutions.
2. Lack of proper legislation and regulation
   - Current laws have been criticised for lack of support for renewable energy projects[64], and for not actively promoting their development. Incentives are not high enough, and funds are mainly aimed at established energy providers, which is disadvantageous for innovative companies entering the market. Also, the absence of standardised rules and minimum technical specifications for design, operation and maintenance, make it difficult for new actors to implement projects.

3. Lack of qualified human capital and environmental awareness
    - The root of this barrier is in the low access to quality education in Colombia. This difference is notable between urban and rural schools, leading to shortage of qualified personnel for renewable energy projects, and to low understanding of environmental issues in the rural regions[64].
4. High investment costs
    - The investment and upfront costs of implementing a renewable energy system in the rural regions can be significantly more expensive than in the urban parts of Colombia[67], and without subsidies the costs are often too high for low-income communities.
5. Misconception of the role of community
    - In order for a renewable energy project to succeed, the community must support and participate in the project. This fact is often neglected by companies and organisations that try to implement out-of-the-box solutions without taking into account local circumstances. Also, communities will maintain a system in the long term only if they receive actual benefit from it in the form of productive use cases.
6. Subsidised diesel generation
    - Historically, the ZNI have received heavy subsidies for diesel, with the majority of the money flowing to electricity providers in the area. In addition, diesel used in the ZNI is free of tax, making it even more lucrative for energy production. Clearly this makes it nearly impossible for renewable energy to compete against[67].
7. Lack of partnerships for development
    - According to the UN, sustainable development requires partnerships between governments, private enterprises and the third sector in order to succeed[68]. The lack thereof was identified as a barrier to renewable energy in Colombia, both in the literature review and the semi-structured interviews that followed. Bad coordination between these entities creates a social barrier, decreasing transparency and collaboration.
8. Informality
    - Implementation of renewable technologies may be hindered by informality if assignments, commitments or responsibilities between different stakeholders are not officially stated. The tasks of each entity become unclear without contracts and documentation, leading to lack of trust. During the interviews, international development agencies were especially concerned about informality in monetary commitments between them and local authorities. In many cases, the informal employment is used to implement projects, leading to problems when such work needs to be monetised.
9. Poverty
    - The ZNI is home to the poorest communities in Colombia, and the lack of income translates low ability to pay for electricity services, making the penetration of renewable energy systems increasingly difficult.

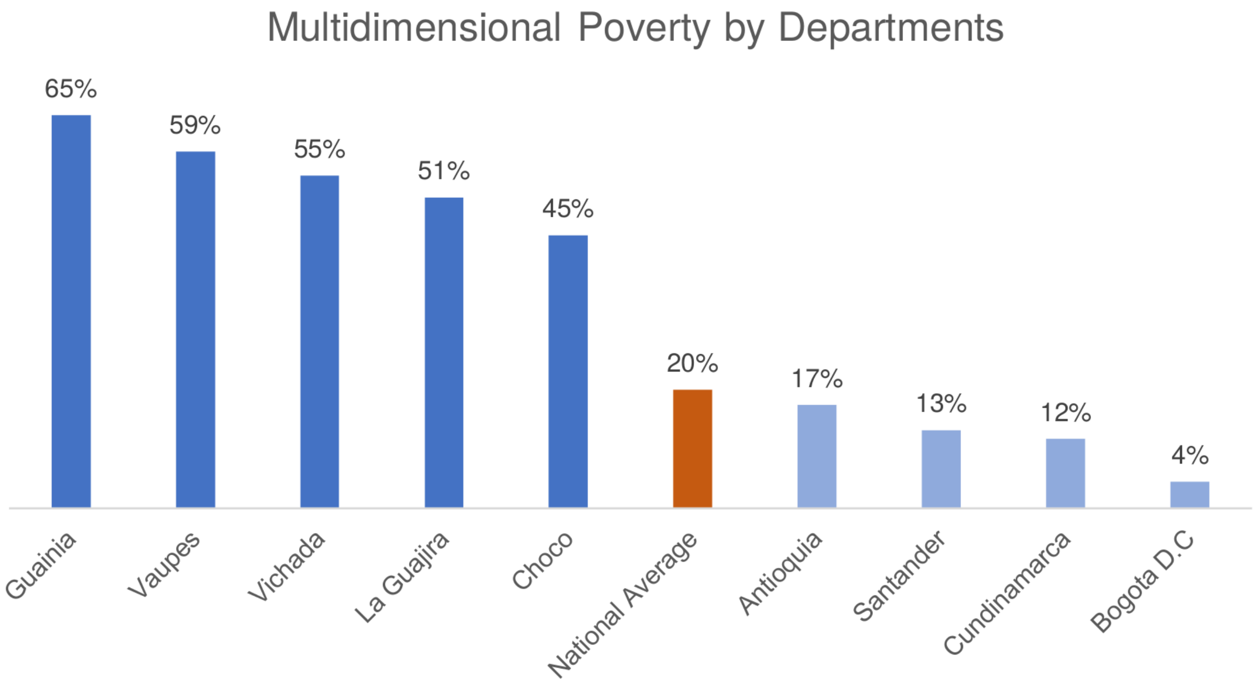


Figure 4.7: Multidimensional poverty in Colombia by department[65].

10. Problems of social order
    - The ongoing armed conflict in some regions of Colombia, combined with thriving illegal activities such as drug trafficking, illegal mining and the black market for diesel represent an enormous risk for renewable energy systems as their advancement would disturb the modus operandi of these groups. The constant threat of violence effectively dissuades both electricity providers and end users from adopting renewable energy.
11. Corruption
    - Corruption is still widely present in Colombia. In the ZNI, it is mostly observed in mid to low levels of local governance, and takes the form of bribes or embezzlement of funds destined for rural development. Bribes are often necessary in order for electricity provider to obtain construction permits.

Many of the identified obstacles to renewable energy are interrelated, and addressing one could have implications for another. It is important to realise that the eleven barriers do not have the same impact in all circumstances. Each renewable energy project is different, and the conditions set be community, government and location vary. Hence the set of factors identified in this study should always be considered in the local context to determine which factors are the most pressing, and hot to overcome the barriers. The findings should be used as a framework to assess individual project to see what must be done in order to guarantee sustainability. Similarly, this framework may be used to study systems already installed to understand why they were or were not successful. In the following, three case studies will be described briefly, and the framework of eleven barriers will be applied to each case study.

Case study 1: Amazonia region and the Amazonas department

In the Amazonia region, three solar parks were constructed between 2016 and 2017, none of which has generated electricity since completion. Further, the Amazonas department is classified as an area of exclusive service because of its strategic location in the eyes of the government. Areas of exclusive service have no free market for electricity. Instead, one company is given a monopoly over generation, transmission, distribution and commercialisation of energy in the whole department. This monopoly is overseen by CREG.

The monopoly operating in the Amazonas is Energía para el Amazonas (ENAM), which has been operational since 2010[69]. Even though the largest cities, Leticia and Puerto Nariño, reportedly have electricity 24 hours a day, this figure drops to between 0 and 12 hours in the rest of the department. Even though ENAM is responsible for the three solar parks that have failed to provide electricity to the region, they were constructed without the consent of ENAM, and no agreement on distribution and maintenance was made. The push to implement renewable energy projects came from MME, and ENAM as the local monopoly had to comply even though it has no interest and no qualifications in the area of renewables. Table 4.8 shows how the framework of barriers has been used to assess the obstacles faced by renewable energy systems in Amazonia.

Table 4.8: The framework of barriers used to assess the Amazonia region.

Barrier	Impact	Comments
`Government absence and lack of proper institutionality`	high	The government's interest was to show that renewable energy projects had been implemented, but no support was given to ENAM for construction nor maintenance. No real interest in the success of the projects was shown.
`Lack of proper legistaltion & regulation`	high	The local monopoly has no minimum share of renewables it has to produce, and there are no regulations in place that would support renewable energy.
`Lack of qualified human capital & environmental awareness`	high	ENAM is not interested in renewable energy and has no technicians qualified in this field. The communities where the solar parks were implemented showed little environmental awareness, as did the interviewed manager at ENAM.

`High investment costs`	medium	In the opinion of ENAM, renewables have higher investment costs and logner payback periods. This is one of the reasons why the company is reluctant to go forward with renewable technology.
`Misconception of the role of community`	high	The projects realised in Amazonia did not consider the needs of the community, and were merely implemented to make the government look as if it was actively working towards sustainable goals. The projects were not accompanied with income-generating activities.
`Subsidised diesel generation`	high	ENAM relies heavily on diesel subsidies, and increasing the share of renewables would decrease the companies revenues.
`Lack of partnerships for development`	medium	There was no co-operation between the government and ENAM, nor other organisations with more expertise on renewables.
`Informality`	low	ENAM stands out in the Colombian context due to its professionalism and good business standards [69].
`Poverty`	high	The communities where the solar parks were installed are very poor and have no means of paying for energy without subsidies. As no subsidies exist for renewable energy, they have to rely on diesel.
`Problems of social order`	low	Illegal groups and drug trafficking is not a pronounced issue in the Amazonas department.
`Corruption`	high	The process of implementing the three solar projects was very opaque, and according to interviewees, the projects existed to boost some candidates in the upcoming departmental elections at the time.

The framework clearly shows that many issues were not dealt with throughout the renewable energy projects realised in Amazonia. A tool like this should have been considered before a decision to implement the project to assess where the problems lie, and how to tackle them.

Case study 2: The Pacific region and El Chocó department

El Chocó has the highest share of people living in extreme poverty in the whole country[70], and is one of the worst hit regions when it comes to the internal armed conflict. As a result, El Chocó is dominated by guerilla groups, drug trafficking and illegal mining[71]. The capital of El Chocó, Quibdo, is the only city connected to the national grid in the department, an the rest are mainly powered by diesel generators. Still, a small number of hybrid hydro-diesel power plants exist. The energy market is free with about 25 electricity providers currently active in the region.

Although some hybrid systems exist, many renewable energy projects have failed in El Chocó as per the interviews carried out in the area. While government disinterest and lack of transparency of the heterogeneous free market were mentioned as some of the reasons as to why renewable energy is not advancing in the region, the threat posed by the illegal groups, and the thriving black market of diesel were the most common explanations for these failures. Based on the findings of the interviews in El Chocó, table4.9 makes use of the barrier framework to assess the hindrances faced by renewable energy technologies in the department.

Table 4.9: The framework of barriers used to assess the Pacific region and the department of El Chocó.

Barrier	Impact	Comments
`Government absence and lack of proper institutionality`	high	Lack of co-ordination between state entities and lack of clarity on ownership of transmission lines and generation infrastructure. The unclear situation has lead to inexistent maintenance and appalling power quality. Companies working in El Chocó are constantly out of diesel because of slow delivery by the government.
`Lack of proper legistaltion & regulation`	high	Due to the unregulated free-market structure, there are no clear rules for competition. The current regulation requires that new companies have to organise their own distribution networks.
`Lack of qualified human capital & environmental awareness`	high	Power generation companies rely on diesel and have no knowledge or qualifications for renewable energy. Communities have no environmental awareness and do not see using diesel as problematic.
`High investment costs`	medium	Companies claim that the capital cost of renewable energy systems make them prohibitively expensive. Insufficient transport infrastructure adds to these costs.

Misconception of the role of community	high	.The majority of the inhabitants of El Chocó are of African and indigenous origin with traditions that have to be considered. The effect of the constant threat of violence must also be taken into account.
Subsidised diesel generation	high	Power generation in the regions is fully dependant on cheap diesel, which makes it hard for renewables to compete.
Lack of partnerships for development	medium	No efficient academic nor private partnership opportunities exist for renewable energy.
Informality	high	Starting a business in El Chocó is complicated due to the lack of standardised procedures and high levels of informality.
Poverty	high	Due to high levels of poverty communities are dependant on cheap diesel and cannot afford renewable energy. There is a prevalent culture of not paying electricity bills, and informal debts to companies are normal.
Problems of social order	high	.El Chocó is dominated by illegal groups which brings a high risk for outsiders promoting renewable energy.
Corruption	high	Chocó is well known in Colombia for its high levels of corruption. Local authorities asking for bribes, and embezzlement of public funds are commonplace.

The framework shows that there are multiple severe obstacles in El Chocó that make the advancement of renewable energies near impossible. Further, many of these problems are out the jurisdiction of individual companies or organisations, and have to be dealt with on governmental levels.

Case study 3: Orinoquía region and the Guainía department

Guianía has the lowest population density in Colombia, and the highest level of multidimensional poverty. The energy sector in the department comprises two companies: GENSA and EMELCE. The former is a nationally operating company, the services of which also form part of the national grid. EMELCE is the departmental monopoly that performs distribution and commercialisation in Guainía. When in the rest of the country EMELCE manages all of the power production, the department's capital Inírida has a more traditional energy market model, with generation carried out by GENSA and the distribution by the EMELCE monopoly. Further, Inírida is a relatively wealthy city with a low unemployment rate as compared with other localities in the ZNI.

In Inírida, 20 per cent of the electricity is solar-based, and the rest comes from diesel. Another city in the department, Barranco Minas, has a renwable share of 10 per cent, while the rest of the department is fully dependent on diesel. As part of the field visit, a solar park near Inírida (called Granja Solar Inírida) was inspected. It was installed by GENSA, and is fully operational. Because of the size and national renown of the company, it was easy for GENSA to find enough credit to install the system in Guainía. They also partnered up with EMELCE that agreed to purchase all power generated by the solar park until 2035. EMELCE also approved the solar park's connection permission which is a necessary requirement for the operation of energy systems. None of the three solar parks in the Amazonas had had their connection permissions approved by a grid operator, which is one of the reasons why they never got operational. Interviewees from GENSA also praised the good co-ordination between all public entities and energy providers involved in the project. Table 4.10 shows the assessment of the Inírida solar park with the framework of barriers.

Table 4.10: The framework of barriers used to assess Granja Solar Inírida in the department of Guainía.

Barrier	Impact	Comments
`Government absence and lack of proper institutionality`	low	Good co-ordination between all state entities involved in the project.
`Lack of proper legistaltion & regulation`	medium	Current legislation divides the energy market into generation, distribution and commercialisation, allowing GENSA to sell its electricity to a third party. Regulators set the prices of electricity.
`Lack of qualified human capital & environmental awareness`	low	GENSA has qualified professionals both in technical and financial areas. The company is committed to promoting sustainable energy sources.
`High investment costs`	medium	GENSA was able to obtain enough funds to pay for the high capital costs. The transportation costs of the solar inverter almost stopped the whole construction.
`Misconception of the role of community`	low	Inírida is wealthier than the rest of the department, and the community was keen on the project.

`Subsidised diesel generation`	medium	GENSA still relies heavily on diesel subsidies. If subsidies were lower, they would have more incentive to install solar power plants.
`Lack of partnerships for development`	medium	Public entities and electricity providers co-operated well, but no official partnerships exist.
`Informality`	low	The project was carried out with professionalism, and good transparency between public and private actors. Informality in Inírida is not as common as in smaller municipalities of the region.
`Poverty`	low	The population in Inírida is urban and does not face the same levels of poverty as the rest of the department. Users have the means to pay for electricity.
`Problems of social order`	low	Guerrillas and drug trafficking are not prominent issues in Guainía.
`Corruption`	low	According to the interviewees, Guainía has low levels of corruption, and the construction was not hindered by problems of this kind.

Many characteristics of Inírida make it easy to introduce renewable energy technologies. No problems of social order, little corruption and high professionalism allow projects to be implemented smoothly. The community appreciates electricity and wants more of it, and they are able and willing to pay for their consumption even without introducing subsidies for renewables. It is clear that many of these characteristics are not something that an individual company can affect, but places like Inírida are optimal for pilot projects that increase awareness in the whole country.

4.3 Summary

A major difference between India and Colombia is the organised crime and problems of social order. There is undoubtedly crime everywhere, but the degree to which armed guerilla groups are intertwined into political decision making and the energy market in Colombia has no parallel in India.

The government of India is clearly more organised to meet the targets the sustainable development goals, and seems to be ahead of Colombia in the process of adopting renewable energy. When public and third sector entities in India find that initial subsidies are not enough to promote clean cooking or renewable energy, in Colombia subsidies are do not yet exist at all. Also, the opinion of the communities seems very different from the studies conducted in both countries. The appreciation for energy in general is high in India, and people want more energy even if it is just to power their TV, Whereas in Colombia some communities have doubts about how electricity will change their lives and prefer to sell their solar panels instead of using them themselves.

In the India study of clean cooking technologies, an adoption-centered approach was taken. All factors affecting the advancement of clean cooking technologies were put into the point-of-view of the end customer and the active role of community. But in many cases it seems that the power is not in the hands of the communities themselves, and thus it makes sense to look at the factors from a more general point-of-view. Thus, the Colombia study concentrated on two things. Firstly, the stakeholders that shape the energy sector in the non-interconnected zones of Colombia, as knowing what entities are active in the area and how they affect the advancement of renewables is key to understanding the problem. Secondly, a set of obstacles was defined, and based on this set, a framework was created. This framework serves to identify the key obstacles for renewable energy systems according to location.

Chapter 5

Effects of power quality on energy systems

To better understand the technical challenges faced by off-grid energy systems in rural areas, it was considered necessary to analyse the power quality of existing installations. This was done, in part, to compare the survey results obtained on communities' opinion of the energy services that they were already receiving, and also to pinpoint factors that need to be taken into account whilst designing new off-grid systems.

5.1 Method

This study was realised in two parts: In the first, power quality measurements were conducted in off-grid installations in Nepal. To compare the results, the power quality of the public grid in Kathmandu was also recorded, along with that of the public grid in Munich, Germany. The analysis of the results was done based on the power quality criteria set by the IEEE standard, and their classification of electromagnetic phenomena in power systems[72].
The second part of the study concentrated on examining the short-term effects of varying power quality on electrical appliances commonly used in rural Nepalese households. These included mobile chargers, diverse light bulbs, television sets and electric kettles. The study was conducted between August 2017 and March 2018 as part of the Master's thesis by Mathias Bottheim.

5.1.1 Power quality measurements

Power quality can be defined as "... any power problem manifested in voltage, current of frequency deviations that results in failure or maloperation of customer equipment"[73]. As per this definition, power quality is seen as a customer-side issue, and should thus be assessed at the consumer end. For the purposes of this project, changes in power quality were further classified into deviations in voltage, frequency and waveform from their nominal values[74]. In European AC power systems, 230 V RMS voltage, 50 Hz frequency and a pure sinewave are considered the nominal or desired power quality, and these three characteristics were subsequently taken as indicators of good or bad power quality in the tested cases. Figure 5.1

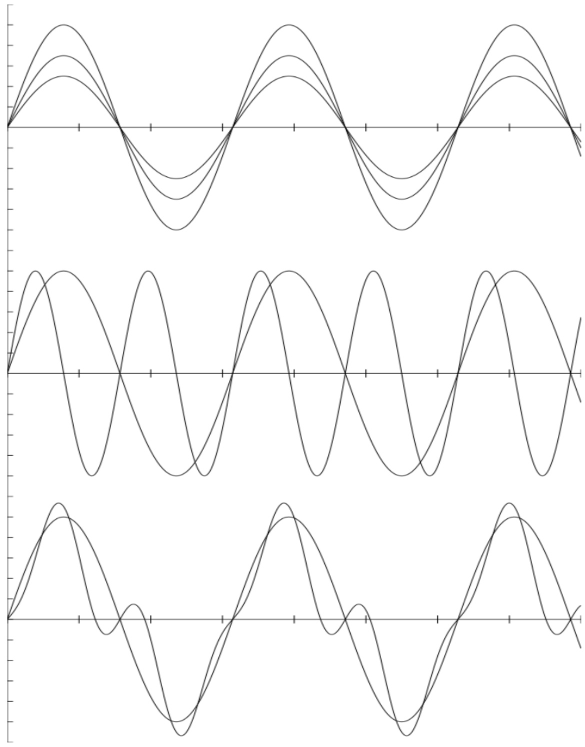


Figure 5.1: Disturbances in wave amplitude, frequency and sinewave form.

shows these three indicators, and how they can deviate from the nominal values. Further, table 5.1 summarises the IEEE classification of electromagnetic phenomena in power systems. The categories are based on the typical duration of each phenomenon and its magnitude.

Transients are typical when generators and other electrical components are connected or disconnected, and have an average duration ranging from nanoseconds to microseconds. So called short-duration RMS variations are more critical to consumers because they have a more perceptible duration, from several seconds up to one minute. If the voltage drops between 10 and 90 per cent of the nominal value, the short-duration RMS variation is called sag. Sags are often caused by brief system failures or by the connection of large loads. The temporary rise in voltage is called a swell, and usually occur when disconnecting loads.

Under and overvoltages are similar to sags and swells but of a significantly longer duration. They are categorised under long-duration RMS variations, and usually arise as variations of approximately 10 per cent of the nominal voltage. These phenomena can also be caused by connecting or disconnecting large loads, respectively. Further, in this research, more severe long-term variations in the negative direction are called substantial voltage drops. In case the voltage drops beneath 10 per cent of the nominal value, the deviation is called an interruption. Depending on the length of the interruption, it is called momentary, temporary or sustained. The habitual causes for momentary and temporary interruptions are equipment failures and control malfunctions. Sustained interruptions often occur due to permanent damage to hardware and need to be fixed manually.

Frequency variations are specified as an increase or decrease as compared to the nominal value. Their classification is also based on the severity of the deviation and the duration of

Table 5.1: Classification of electromagnetic phenomena in power systems[72].

Category	Typical duration	Voltage magnitude
1.0 Transients		
1.1 Impulsive		
1.1.1 Nanosecond	< 50 ns	
1.1.2 Microsecond	50 ns - 2 ms	
1.1.3 Millisecond	> 1 ms	
1.2 Oscillatory		
1.2.1 Low frequency	0.3 - 50 ms	0-4 pu
1.2.2 Medium frequency	20 μs	0-8 pu
1.2.3 High frequency	< 5 μs	0-4 pu
2.0 Short-duration MRS variations		
2.1 Instantaneous		
2.1.1 Sag	0.5-30 cycles	0.1-0.9 pu
2.1.2 Swell	0.5-30 cycles	1.1-1.8 pu
2.2 Momentary		
2.2.1 Interruption	0.5 cycles - 3 s	< 0.1 pu
2.2.2 Sag	30 cycles - 3 s	0.1-0.9 pu
2.2.3 Swell	30 cycles - 3 s	1.1-1.4 pu
2.3 Temporary		
2.3.1 Interruption	3 s - 1 min	< 0.1 pu
2.3.2 Sag	3 s - 1 min	0.1-0.9 pu
2.3.3 Swell	3 s - 1 min s	1.1-1.2 pu
3.0 Long-duration MRS variations		
3.1 Interruption, sustained	> 1 min	0.0 pu
3.2 Undervoltage	> 1 min	0.8-0.9 pu
3.3 Overvoltage	> 1 min	1.1-1.2 pu
3.4 Substantial voltage drop	> 1 min	0.1-0.8 pu
4.0 Waveform distortion		
4.1 DC offset	steady state	0-0.1%
4.2 Harmonics	steady state	0-20%
4.3 Interharmonics	steady state	0-2%
4.4 Notching	steady state	
4.5 Noise	steady state	0-1%
5.0 Power frequency variations	< 10 s	+/- 0.1 Hz

the phenomenon. Further details of the frequency deviation categories are show in table 5.2. The waveform of an AC signal should be a pure sine wave in the nominal case. However, transients can occur as short-lived peaks distorting the sine form. The transients are divided into two categories, namely impulsive transients and oscillatory transients. The former is characterised by sharp peaks in the positive or negative direction, after which the original waveform is resumed. The latter consists of sudden peaks that oscillate with high frequency before gradually fading away.

Another frequency phenomenon is harmonics and interharmonics that are sinewave signals with frequencies that are multiples of the nominal frequency. The harmonics distort the

Table 5.2: Classification of frequency deviations in power systems[72].

Category	Typical duration	Frequency magnitude
`1.0 Temporary interruptions`	10 s - 1 min	< 0.1 pu
`1.1 Sustained interruptions`	> 1 min	0 pu
`2.0 Overfrequency`	> 1 min	1.1-1.2 pu
`2.1 Underfrequency`	> 1 min	0.8-0.9 pu
`3.0 Temporary sag`	10 s - 1 min	0.1-0.9 pu
`3.1 Temporary swell`	10 s - 1 min	1.1-1.2 pu
`4.0 Substantial frequency drop`	> 1 min	0.1-0.8 pu
`4.1 Substantial frequency peak`	> 10 s	> 1.2 pu

waveform and decrease the total power output. Harmonic distortion is usually expressed as the total harmonic distortion (THD) value:

$$THD = \frac{\sqrt{(V_2^2 + V_3^2 + \cdots + V_n^2)}}{V_1} \times 100\%, \tag{5.1}$$

where all voltage values are given as RMS values, and V_1 is the RMS voltage of the fundamental frequency.

To measure the three key variables for power quality defined above, a wide range of equipment was used. The RMS voltage was logged with a dedicated datalogger from Scanntronik with a 2 kHz sampling rate. Additionally, a self-developed datalogger was used to measure both RMS voltage and frequency. The device was a proof-of-concept of a low-cost Arduino-based datalogger, and capable of recording at five-second intervals. The device is shown in figure 5.2.

The power quality measurements were realised in two remote locations in the Manang district of rural Nepal, both of which receive their electricity from small-scale hydro power plants. Further, only AC power systems were considered as they are currently the norm in Nepal.

The first location is the Lophelling Boarding School (LBS) near the city of Humde, situated at an altitude of 3350 meters. The school and various villages in the region receive power from the Sabje power station with 80 kW maximum capacity. The second location is the village of Chame at 2650 meters. The village is supplied by the Chame power station with 45 kW capacity. This station supplies power to Chame only. The technical details of both power stations have been gathered into table 5.3. The on-grid measurements were taken from the public grid of Nepal, in the district of Thamel in Kathmandu, and from the German public grid in the inner-city area of Munich. Figure 5.3 shows the Nepalese measurement locations on a map.

5.1.2 Analysis of effects of power quality on common consumer appliances

In order to assess the direct effects of bad power quality on consumers in off-grid energy systems, it is not enough to concentrate on the electromagnetic phenomena alone. In addition to dissatisfaction in intermittent service, customers may experience failure of components in their electrical appliances. To discover whether this is a risk in existing off-grid hydro power systems, a selection of commonly used electrical devices was subjected to poor power quality,

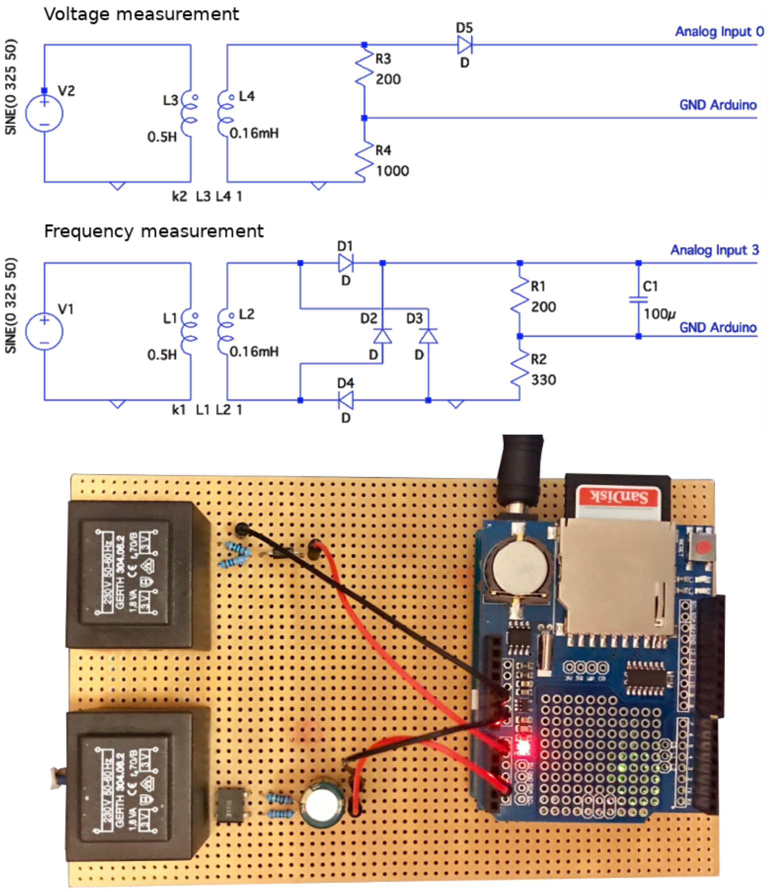


Figure 5.2: Self-built Arduino-based datalogger.

Table 5.3: Key parameters of the analysed power stations.

`Station`	Sabje	Chame
`Power capacity`	80 kW	45 kW
`Flow rate`	380 l/s	180 l/s
`Net head`	35 m 6 59.3 m	
`Turbine`	2 crossflow turbines by Thapa Engineering Industries (P)Ltd., Nepal	crossflow turbine by Thapa Engineering Industries (P)Ltd.
`Generator`	3-phase AC synchronous generator by Kerala Electrical and Allied Engineering Co.Ltd., India	3-phase AC synchronous generator by BHEL Electrical Machines Ltd., India

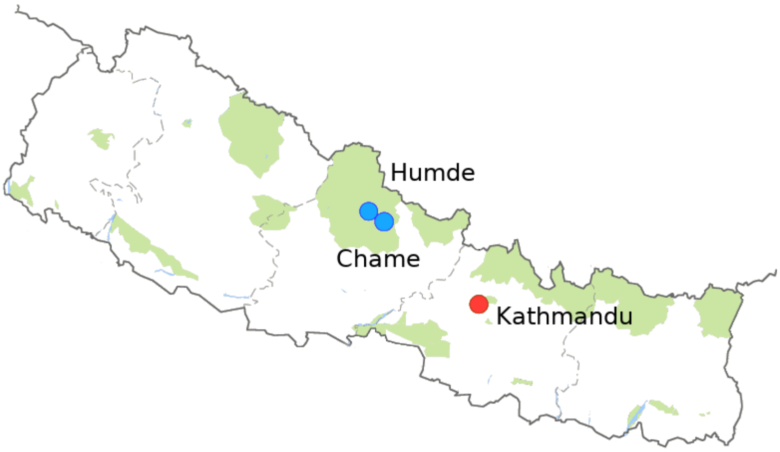


Figure 5.3: Location of Humde, Chame and Kathmandu on the map[26].

and examined for their behaviour under these conditions. First, the chosen appliances were classified into three groups based on their impedance characteristics, namely resistive loads, inductive loads and electronics. Table 5.4 elaborates on the defined categories. Capacitive loads will only be covered as part of the electronics category because their role as consumer load is not significant. In AC grids, the impedance of a component consists of two parts: resistance (real part) and reactance (imaginary part):

$$Z = R + iX, \tag{5.2}$$

where Z is the impedance, R the resistance and X the reactance. i is the imaginary unit. Similarly, the power flowing in an AC system also comprises a real and an imaginary part. Their sum is called the apparent power S, and defined as follows:

$$S = P + iQ, P = VI \cos\phi, Q = VI \sin\phi, \tag{5.3}$$

where P is the active power, Q the reactive power, and ϕ the phase angle between voltage V and current I. Using the above definitions, the ratio between the active and reactive power, or power factor PF, may be computed:

$$PF = \frac{P}{|S|} \tag{5.4}$$

The appliances were tested under similar conditions to those determined by the on-site power quality measurements. These conditions were established artificially in the laboratory, and to this end, an experimental setup was designed. Figure 5.4 shows a block diagram of the setup. The effects of changing voltage and changing frequency were tested separately, and the voltage experiment is represented with black blocks in the figure. The frequency experiment is represented with blue blocks.

For the voltage experiment, an isolation transformer with a voltage range of 0-250 V AC was used, allowing for the simulation of negative and positive voltage deviations. The maximum power output of the transformer is 1 kW. For the frequency experiment, a frequency inverter was connected to an asynchronous motor driving a synchronous generator. The output of the

Table 5.4: Classification on electrical appliances.

Load type	Description	Example
`Resistive loads`	Loads consisting only of heating elements. The impedance only has a real part, and the power factor is 1	Incandescent light bulbs, electric kettles
`Inductive loads`	Mainly loads with inductive motor. The impedance has both a real and an imaginary part, and the voltage leads current in phase	Fans, compressors, refrigerators
`Electronics`	Loads with switched-mode power supplies. Use DC power, and comprise a rectifier and a control circuit to adapt voltage levels	Mobile chargers, laptop chargers

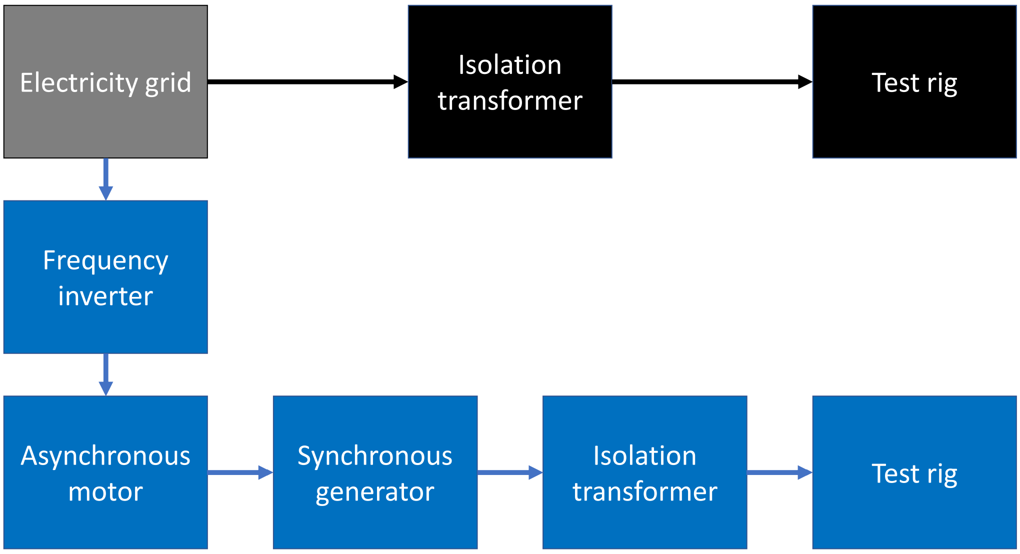


Figure 5.4: Block diagram of the test setup. The blue blocks indicate the frequency experiment, and black blocks the voltage experiment.

generator was then connected to the isolation transformer to provide the input for the test rig. The test rig itself consisted of five parallel connected sockets with a switch and terminals to connect voltage meters. Additionally, each socket has a special bulb socket for standard Nepali light bulbs. An image of the test rig is provided in figure 5.5.

The test conditions were subject to the results obtained from the on-site power quality measurements and are presented above in section 5.1.1.

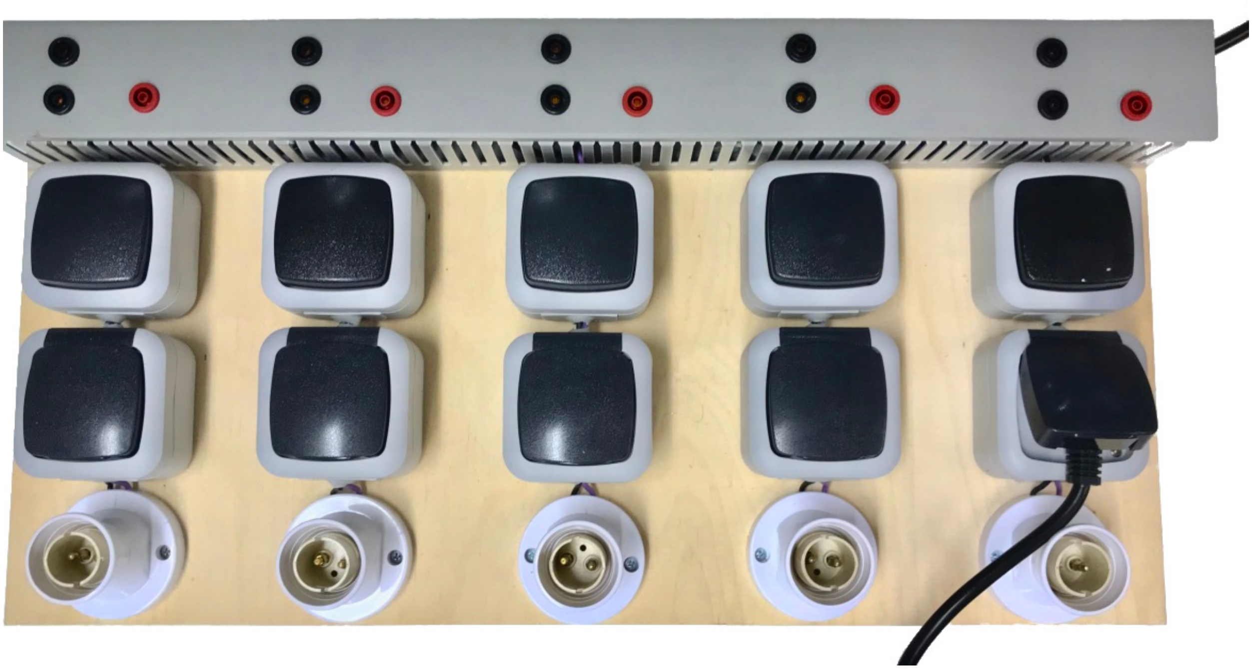


Figure 5.5: Self-built test rig with parallel sockets.

5.2 Results

5.2.1 Power quality measurements

As discussed in section 5.1.1, this study defines power quality with three indicators, namely the RMS voltage, the frequency, and the sinewave from of the AC voltage signal. Power quality was measured at two off-grid locations in Nepal and compared to similar measurements taken from the national grid in Kathmandu as well as Munich, Germany, for an improved reference. The on-site measurements show that the off-grid power quality is very low compared to that of the on-grid reference locations. Substantial deviations in voltage and frequency were recorded in both directions, with a strong tendency to be lower than their nominal value.

The self-made low-cost datalogger introduced in section 5.1.1 was validated by comparing its measurements with those obtained with a high-end multimeter. The comparison is visible in Figure 5.6. As the devices showed essentially the same accuracy in both measurements, the low-cost datalogger was proven to be a viable alternative to expensive commercial measurement equipment. Thus, the rest of the measurements shown in this section are, where applicable, those conducted with the self-made datalogger.

Figures 5.7 and 5.8 show the results for voltage and frequency in the on-grid reference sites (Munich and Kathmandu) over a week of constant measurements. Clearly, the power quality in Munich is very good in general. The Voltage trend looks stable, staying within a range of 12 V (226 V to 238 V) over the whole week. Further, no interruptions in power supply were detected. The frequency looks extremely stable around the nominal frequency of 50 Hz. It moves within a 0.30 Hz interval along the course of the recording. The highest share of values seem to stay

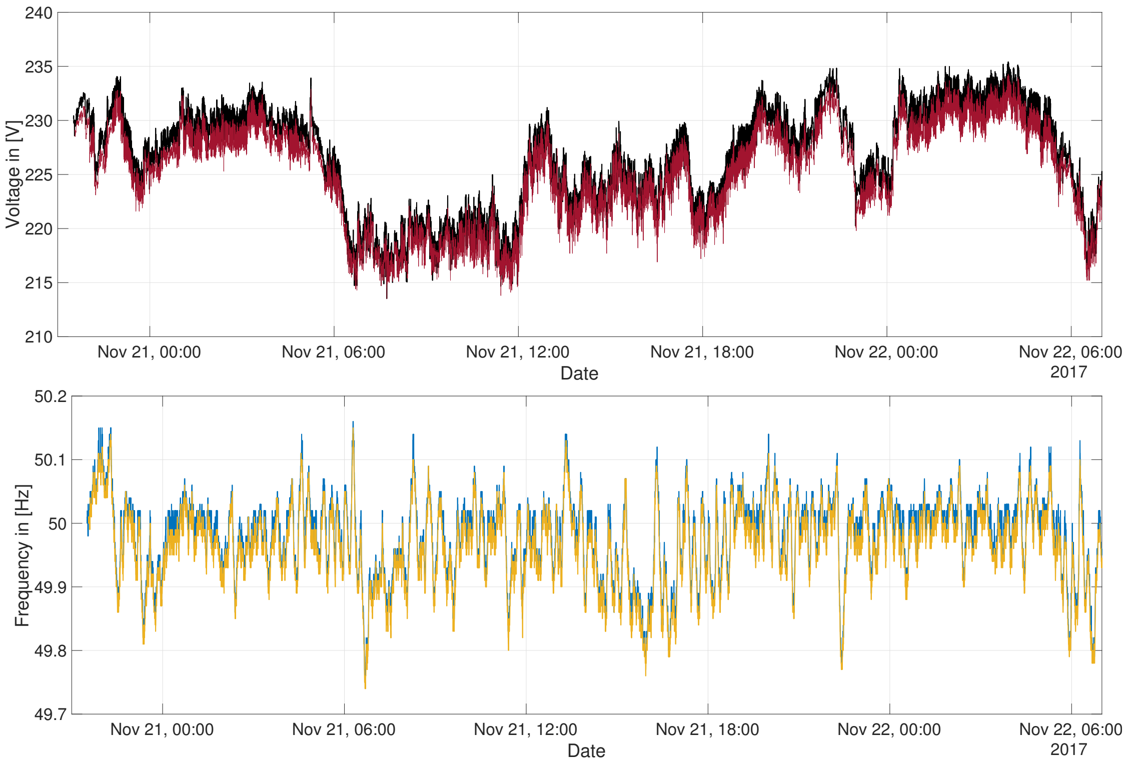


Figure 5.6: Voltage and frequency measured with the self-made datalogger (black and blue) and a commercial multimeter (red and yellow).

within $\pm0.05Hz$ of the nominal frequency, which is a clear indicator of good power quality. Compared to Munich, the results from Kathmandu show more instability in the grid, although the voltage is held in the desired range to a certain extent. Apart from five power outages over the course of the measurement, the voltage stays in the 200 V to 250 V interval. Similarly, the frequency stays around the nominal value of 50 Hz for most of the time. Still, even short power outages may lead to problems where constant power supply in essential, and is certainly detrimental to end-user satisfaction.

Figures 5.9 and 5.10 display the voltage and frequency measurements from the two off-grid measurement locations, Chame and the Lophelling Boarding School (LBS), respectively. Substantial grid instability was experienced at both locations with frequent and sustained power outages. These interruptions of the power supply are almost a daily occurrence and last from a few minutes to several hours. In the case of LBS, the last interruption in the measurement took over 24 hours.

In both off-grid scenarios, voltage and frequency deviated wildly from the nominal values. Deviations to lower values are far more frequent than peaks, even though the latter also occur. In the Chame results, the voltage is seen to range from 80 to about 240 Volts, and the frequency is anywhere between 25 to 70 Hz when the power is on, and obviously zero during the power outages. At LBS, voltages as low as 50 Volts were measured, accompanied by a frequency ranging from 30 to 70 Hz.

Despite the substantial deviations in voltage and frequency, the off-grid locations showcased

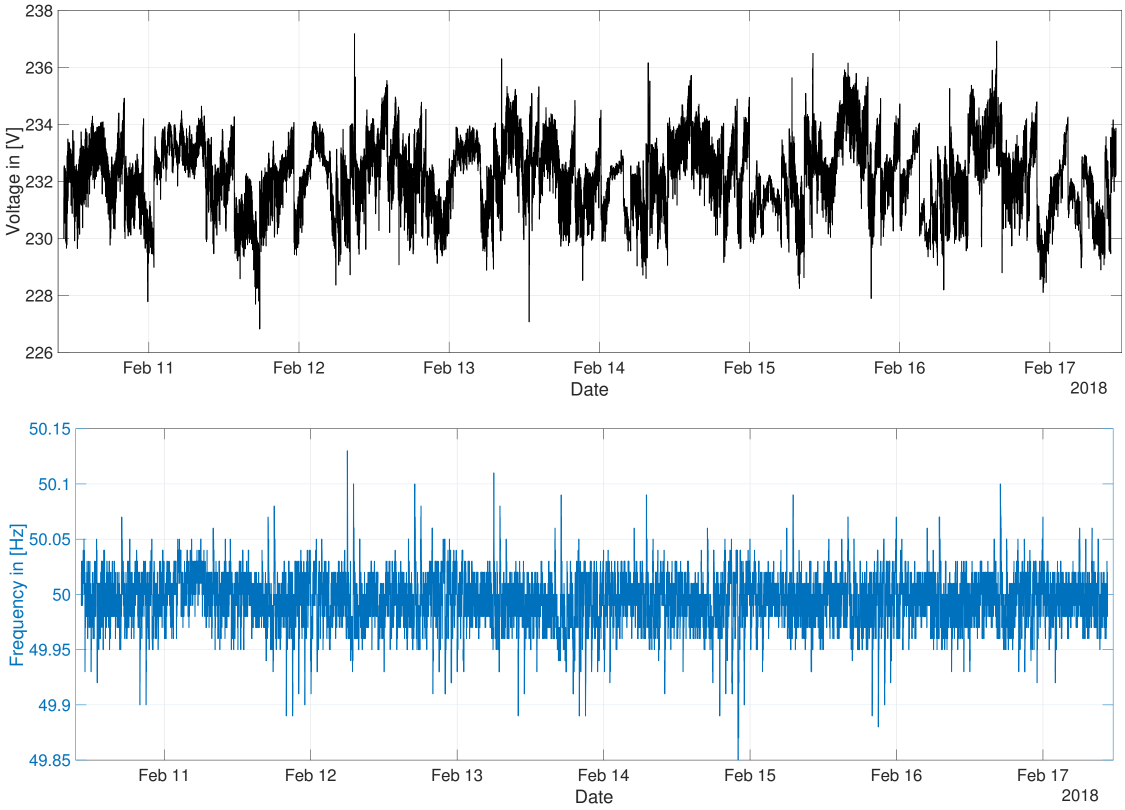


Figure 5.7: Voltage and frequency fluctuations in the German national grid in Munich, over a period of one week.

an almost ideal sinewave form throughout the measurement period. Interestingly enough, by far the worst sinewave was seen in Munich, most likely due to the high number of power electronic components connected to the German main grid. Figure 5.11 displays the results of the sinewave measurements in the off-grid and on-grid locations. In Munich, the voltage signal is not as smooth as the ideal sinewave and it shows oscillations of higher harmonic order within the fundamental.

5.2.2 Analysis of effects of power qulaity on common consumer appliances

In this part of the study, experiments with deviations between 50 and 110 per cent of the nominal voltage were conducted in 5-per cent steps for most of the appliances. If the tested unit stopped working at a certain voltage, further voltage deviations in that specific direction were not to be performed as the appliance presumably either did not have enough power to function, or had failed. Selected loads were be exposed to more extreme levels of deviation.

Frequency deviations were tested from 42.5 Hz up to 65 Hz. As the supply voltage generated by the synchronous generator reduces with decreasing frequency and the isolation transformer has a limit for boosting up the voltage, the setup for frequency deviation did not allow for more extreme deviations in the negative direction. Seeing that the sinewave form is almost ideal in the off-grid systems visited, no tests with varying levels of distorsion were conducted. See

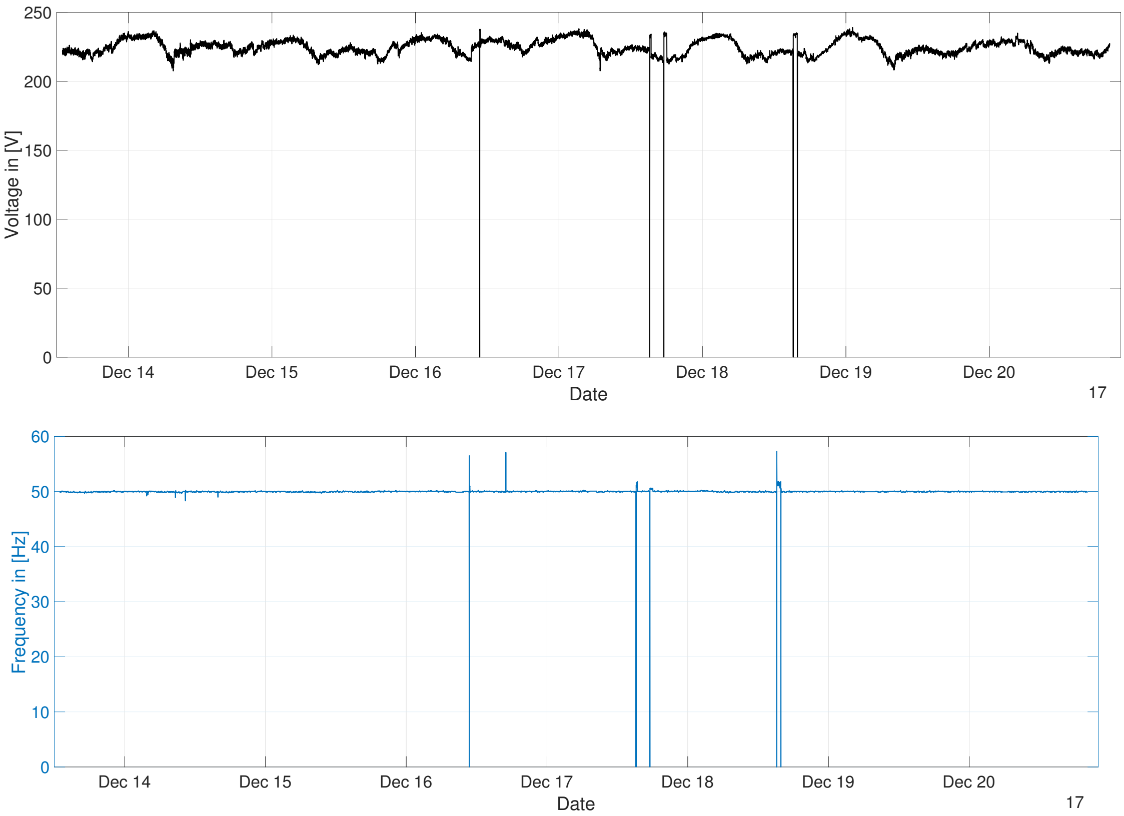


Figure 5.8: Voltage and frequency fluctuations in the off-grid power system of Chame over a period of one week.

figure 5.4 fur further details of the test setup.
Both the voltage and the frequecy were studied independently, keeping one constant whilst varying the other. Depending on the tested appliance, various input and output quantities were measured. Input power, power factor and THD[1] were determined for all devices, and appliance-specific quantities included illuminance for lighting sources (resistive and LED), time taken to boil water for the electric kettle and rice cookers, and output voltage and power for the power supplies (mobile charger and tv).
The illuminance was measured by placing a given lightbulb inside a box (approximately $25cm \times 15cm \times 15cm$) with a sensor pointed straight at the light source. Hence the illuminance values presented in the following chapter are not directly comparable with universal lighting recommendations for rooms, but still give good comparative results.
Resistive loads in this test comprised of incandescent light sources and various cooking devices. Due to their similar characteristics, only results for the incandescent lightbulb and one type of cooking device (300W rice cooker) are displayed. Unsurprisingly, in the case of resistive load, the power factor stayed constant at 1, as there were no inductive or capacitive components in the circuit. Similarly, the THD of the current was minimal at 1.3 per cent, originating from the German main grid itself, rather than the tested appliance. Clearly, resistive loads are very tolerating towards fluctuations in power quality.

---

[1] Total harmonic distorsion.

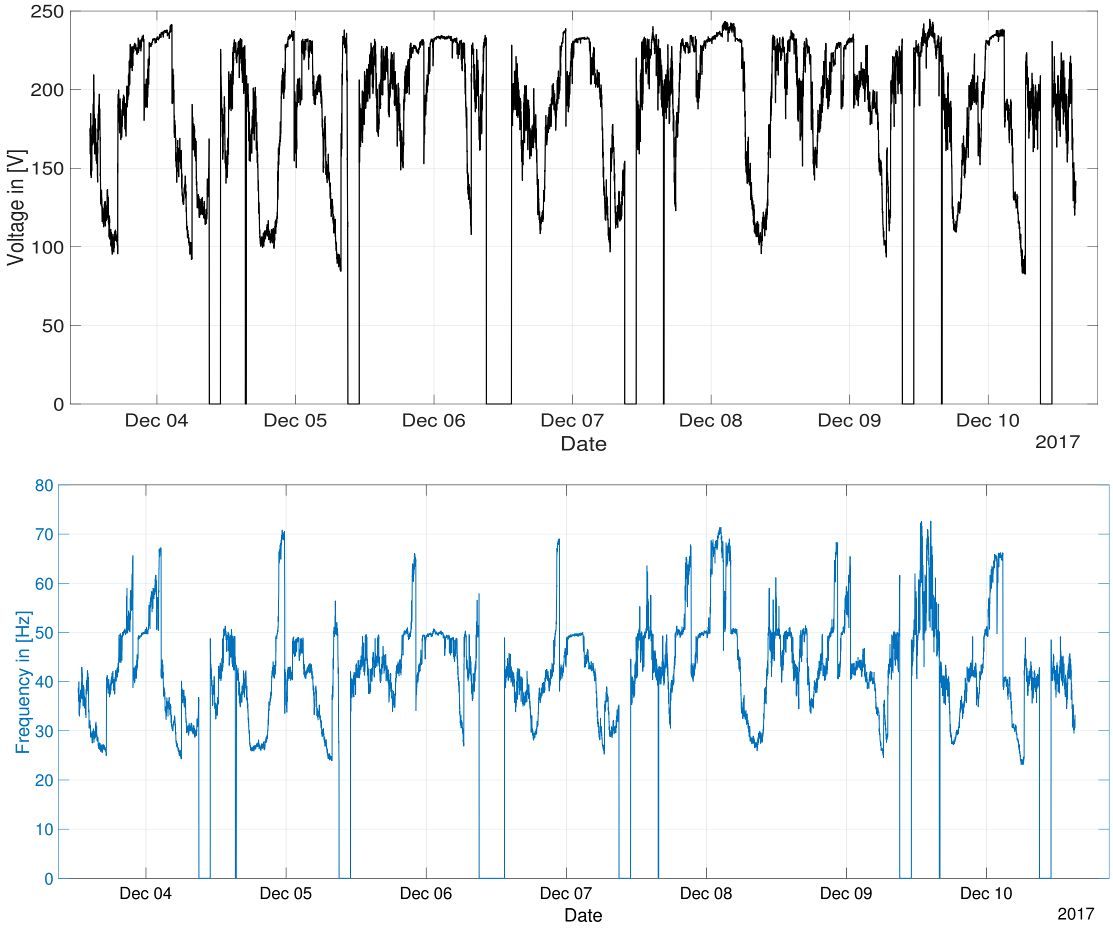


Figure 5.9: Voltage and frequency fluctuations in the off-grid power system of Chame over a period of one week.

As seen in Figure 5.12, the illuminance of incandescent bulbs drops in a linear fashion with decreasing voltage, resulting in direct decline of comfort from the point of view of the consumer. Flickering lights are irritating and may cause headaches and problems in concentration. The three lines seen in the image correspond to three different bulbs of the same brand.

The lower image in Figure 5.12 shows how the time needed to boil water with a rice cooker is also linearly dependent of the grid voltage. The 300 W rice cooker experiments were conducted with 500 ml of water and started at the exact same temperature of 28 centigrades for every voltage/frequency level.

With the nominal RMS voltage of 230 V, the time to boil was about 12 minutes, but rose to over 30 minutes when the voltage dropped to 150 V. Clearly this can affect the acceptance of electrical cooking methods in a rural household, as was seen in the surveys previously conducted in Nepal (see section3.1.2). If cooking with electricity takes longer than with traditional biomass, people will naturally be less eager to adopt the former.

The frequency of the grid had no influence on either the illuminance of resistive lighting or the boiling time of water with resisitive cooking equipment.

In this category of switched-mode power supplies, two types of tv sets (CRT and LED) and two

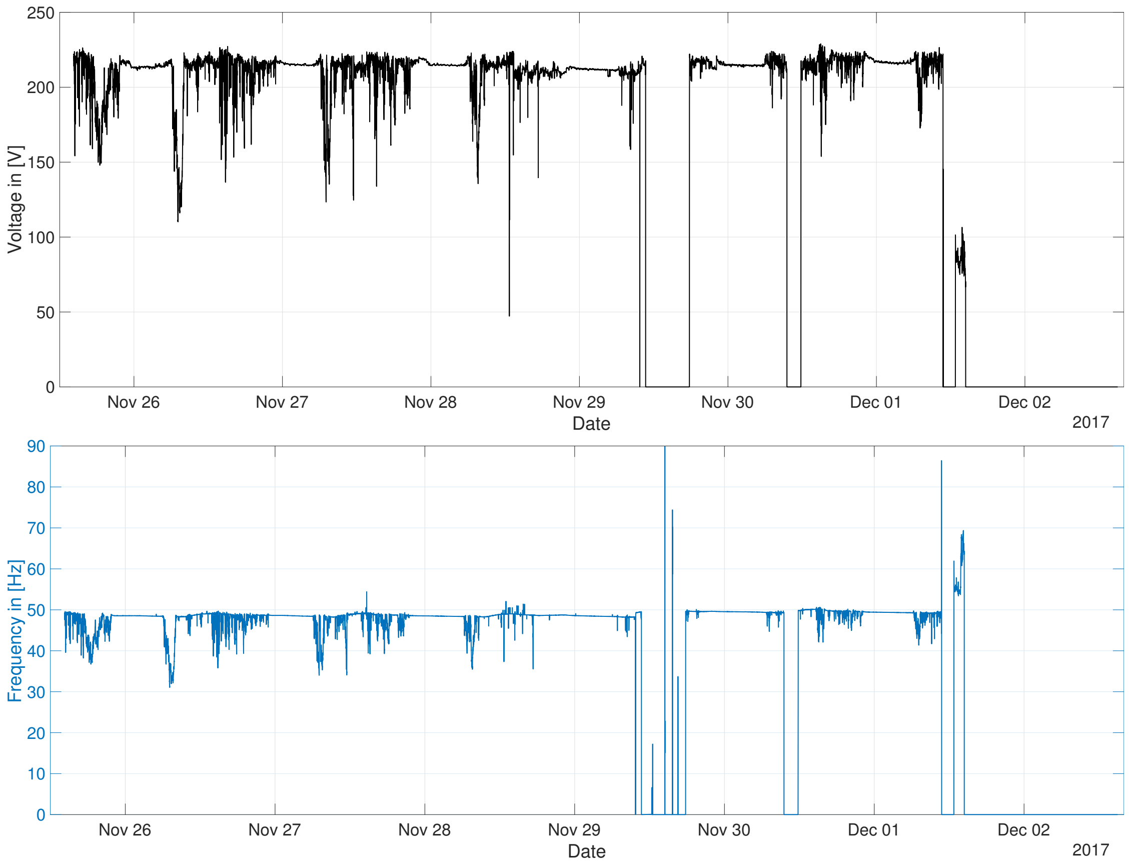
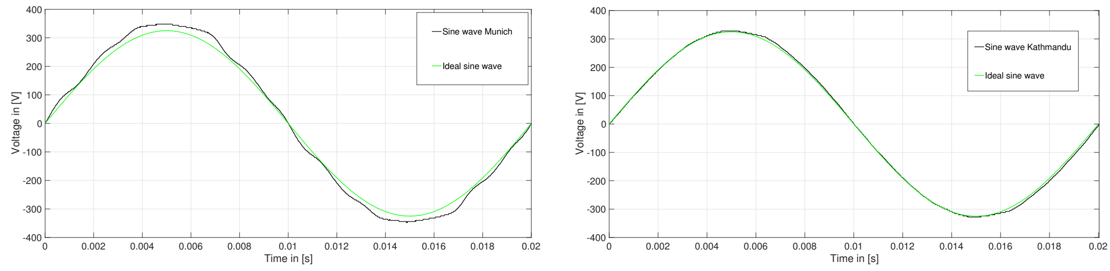
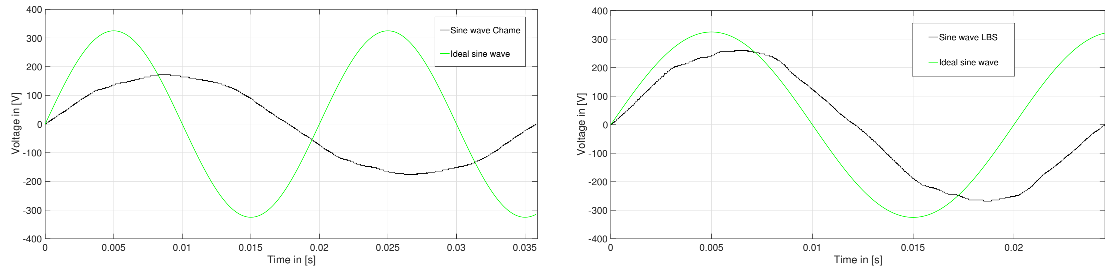


Figure 5.10: Voltage and frequency fluctuations in the off-grid power system of LBS over a period of one week.



Munich

Kathmandu



Chame

Lophelling Boarding School

Figure 5.11: Sinewave form at all measurement locations compared to the reference wave of 50Hz.

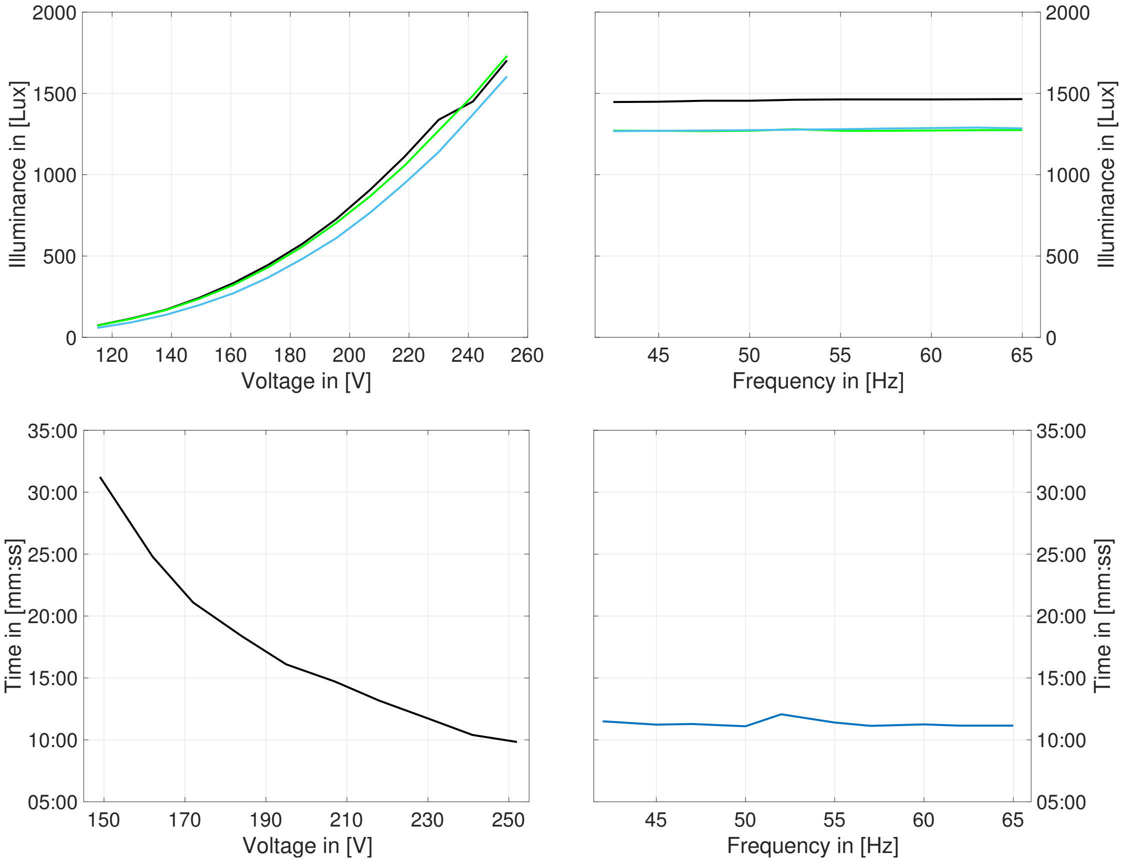


Figure 5.12: Above: Illuminance of incandescent bulbs. Below: Time for water to boil in rice cooker

types of mobile charger were tested. Due to the similarity of the results for the tv's, only those of the LED tv are shown in Figure 5.13. For both tv's, their input power increases slightly with increasing grid voltage, and the power factor decreases. The output power of the tv's power supply was constant irrespective of voltage and frequency. The THD of the input current also increases with higher voltage, from 133 to 156 per cent for 104 and 253 Volts, respectively, for the LED tv. For varying frequency, no such systematic change was detected.

In the central image of Figure 5.13, the power output of a local brand of mobile charger is displayed. All three units failed to maintain a constant power output with decreasing voltage, and similarly to the tested tv's, both the input power and THD grew with rising voltage level. The power factor tends to decrease, ranging from 0.34 to 0.48.

The high-end mobile charger of a multinational brand was capable of providing constant power output despite the changes in voltage or frequency. The THD and power factor were affected in the same manner as when testing the cheap local brand. Again, frequency did not seem to affect the output power at all.

In the final category, other lighting loads, namely LED and CFL light bulbs, were tested. Looking at Figure 5.14, it is clear that the LED bulbs effectively provide constant power irrespective of the grid voltage. The illuminance varied minimally compared to the incandescent bulbs shown

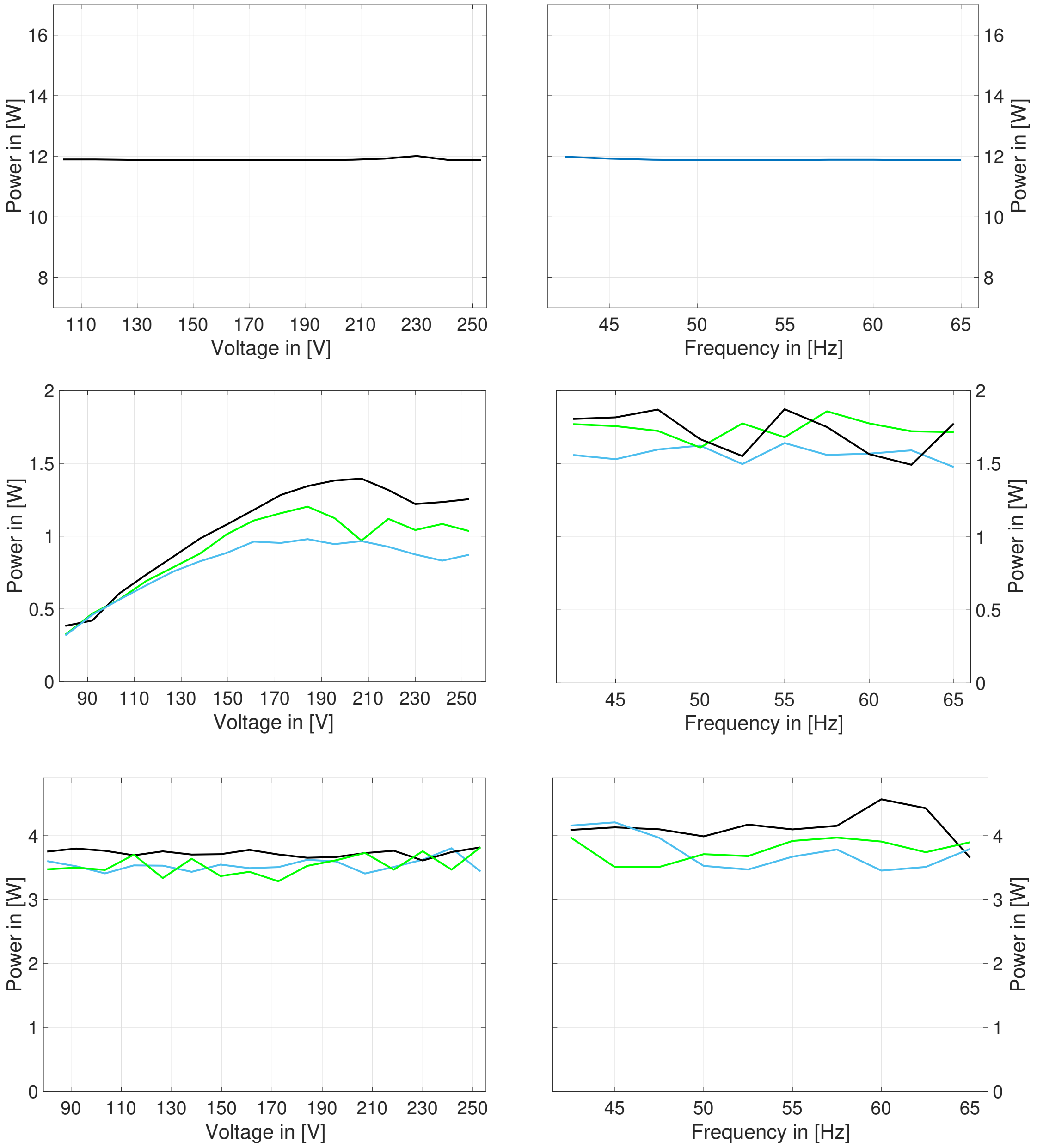


Figure 5.13: Above: Output power of power supply of LED tv. Centre: Output power of local brand of mobile charger. Below: Output power of high-end mobile charger.

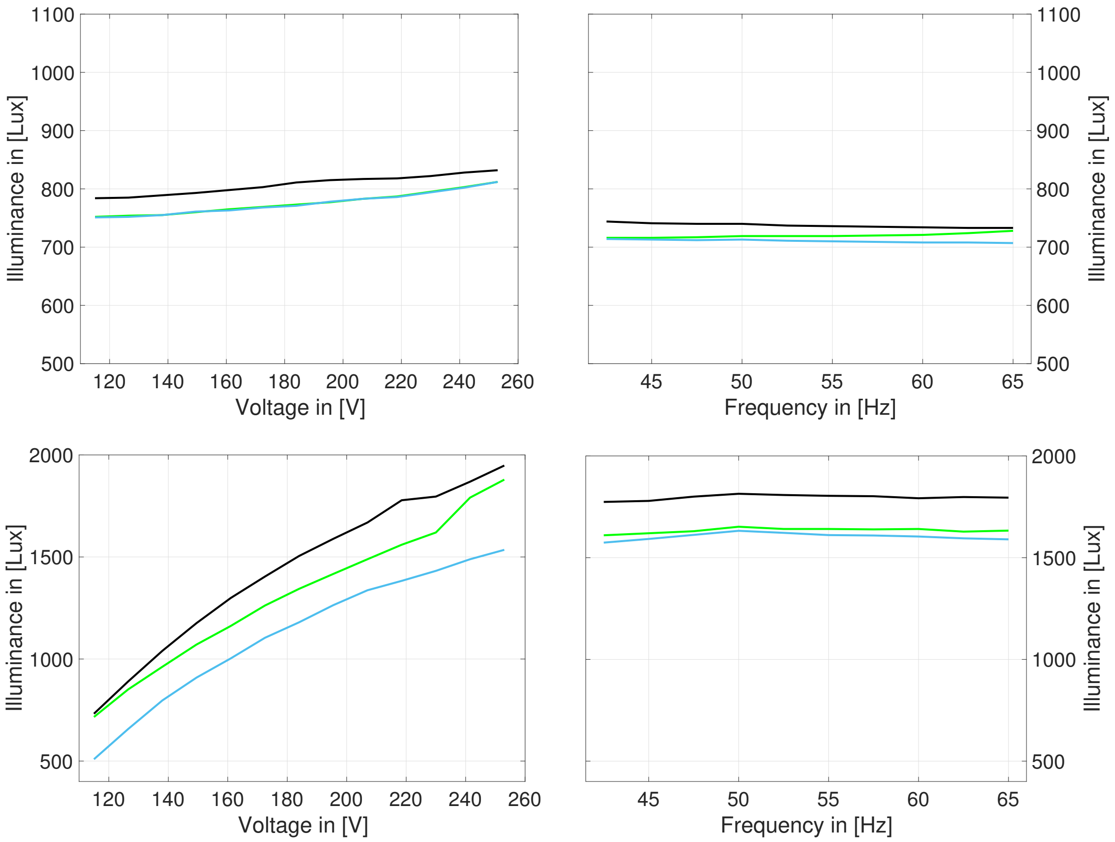


Figure 5.14: Above: Illuminance of LED bulbs. Below: Illuminance of CFL bulbs

at the top of Figure 5.12 and the CFL lights. From the point of view of lighting, frequency again seemed unproblematic. For LED lights, a slight decrease in power factor was detected with increasing voltage. At the same time, the THD value rose. Input power, however, stayed more or less constant, ranging from 4.5 to 4.6 W.

The CFL light bulb showed different behaviour. As with incandescent bulbs, the illuminance dropped linearly with decreasing voltage. The input power fell from 14.0 W at 253 V to 6.8 W at 115 V, and the input current stayed constant at 0.09 A. Just as before, the power factor decreased with increasing voltage and the THD rose.

5.3 Summary

Power quality is important especially from the consumer point of view as the lack of it may dissuade people in low-income groups from adopting connections. Continuing to use traditional fuels is detrimental to health and insufficient to boost the local economy. The lack of access to modern energy services is one of the major obstacles to socio-economic development [2].

This study showed that the status quo of power quality in the existing off-grid installations in Nepal is dreadful, and tha it is mainly caused due to insufficient power supply. The frequent power outages alone are enough to discourage locals from opting for electricity services but the effect of fluctuating voltage and frequency on household appliances may cause a further disincentive to pay for energy.

The experiments conducted on common electrical appliances clearly showed that frequency does not affect the functionality of the most frequently used devices. The fluctuating voltage, however, causes resistive appliances such as incandescent bulbs and cooking devices to underperform, decreasing consumer comfort and taking time from other activities. Without improving the reliability of the power supply, this type of appliances cannot be adequately used. Switching-mode power supplies and LED-based appliances show little deterioration in their functionality even with varying voltage level. Thus they are a very good option in existing power-systems with no sophisticated control system. Further, communities receiving electricity for the first time usually underline the importance of having access to lighting and television [75]. In such scenarios, if cost is a major concern, a microgrid could be constructed even without an efficient control system as long as only LED-based light bulbs and tv sets are used. The added advantage of such an approach is that LED loads need a fraction of the power used by more conventional appliances. Incandescent light bulbs, for example, reach ratings up to 100 W whereas LED bulbs are usually in the range of 3 to 9 W. Similarly, the LED tv tested as part of this study only draws around 12 W compared to the 35 W needed by the CRT tv. In so doing, consumers could significantly decrease their power consumption, or alternatively connect far more loads than before.

On the other hand it is evident that power outages are always undesirable and even the most rudimentary energy management systems should aim to eliminate them to improve end-user satisfaction. Further, as soon as the need of a rural household grows, power quality will become an issue beyond power disruptions only. Especially if cooking devices are acquired, an intelligent control system becomes more and more necessary.

Chapter 6

Discussion

In the past three chapters, five studies were presented, all assessing different aspects of renewable off-grid energy systems in a rural setting. The first two concentrated on defining the current energy need in the rural, low-income regions of Nepal and India. It was shown that, in many cases, the ability and willingness to pay for electricity is already present in these remote communities, and that the main obstacle preventing them from obtaining access to electricity is the insufficient supply. Whether due to the disinterest of the central government or because of the locals' lacking awareness of possible energy solutions, the shortage of electricity forces users to stow away their televisions and rice cookers. Bad power quality was also identified as a key factor reducing people's interest in electricity. Paying for a service that is, at best, insufficient damages the general opinion towards that service, and leads to more and more households opting out of electricity, even in places where grid connection is already possible. These two studies also introduced the notion of productive use cases as essential to the success of off-grid energy systems. Productive use cases are income-generating activities that would be enhanced by introducing electricity, thus increasing profit and ensuring that the installed microgrid has value to its users. The results from both Nepal and India suggest that productive use cases are already present in the surveyed communities, and that locals are aware of and appreciate the potential benefits of improved energy access. Further, as indicated by the study of factors affecting adoption of clean-cooking technologies in India and renewable energy systems in Colombia, community awareness and positive opinion towards the new technology is essential for long-term adoption. In the same way, activities promoting socioeconomic growth were found crucial for lasting embracement of technological innovations. Studying the obstacles faced by sustainable innovations showed that the issues are multidisciplinary, and occur at numerous levels of society. Both studies concentrated on the context of rural communities, but approached the topic from different angles. The study of clean cooking in India took a more consumer-centric view, mapping all affecting factors onto the process of consumer adoption. It was found that many obstacles occur at specific stages of adoption, from when potential users are introduced to a new technology for the first time, to when it has already encountered initial adoption. However, some issues such as gender inequality or lack of education span across the whole model, affecting each step of the process. While this approach is valuable to understand the timeline of adoption and when certain issues need to be tackled in order to reach long-term acceptance, it does not provide a clear view of responsibility. To obtain a better perception of who should be doing what to advance sustainable technologies, a stakeholder assessment is needed. The study on Colombia achieved just that in the context of renewable energy systems.

After creating an exhaustive list of stakeholders in the non-interconnected zones of Colombia, the impact of each entity in the energy sector was analysed. This analysis offers better insight of what can and should be done by each of these entities in order to promote renewable energy in the region. Secondly, a set of the most impactful obstacles for renewable energy systems was put together. With this list of barriers, an assessment in the target community can be made to see which obstacles are the most pressing locally. Combining the results with the list of stakeholders, a wholesome picture of local needs and responsibilities may be constructed.

Some of the results of each of the four above-mentioned studies overlap and complement each other heavily. Many of the reasons mentioned by the Nepalese and Indian households as to why they have not yet received electricity resonate strongly with the factors identified in the subsequent studies of India and Colombia. High investment costs due to difficult terrain and long distances were found to be problematic in each of the four studies. The failing subsidy system for LPG in India and for diesel in Colombia have similar consequences, making it hard for newer, non-subsidised technologies to compete. Further, parallels may be drawn between obstacles for the advancement of clean cooking and those faced by renewable energy technologies. Many of the identified factors from innovation awareness to community involvement and maintenance plans are general issues affecting any new technology.

Throughout the interviews, multiple anecdotes were shared of projects with sound business plans and good intentions that failed because of insufficient communication with the affected community. These findings suggest that active communication and trust between the community and the parties promoting renewable energy are essential to ensure a positive outcome. Based on the review literature, table 6.1 shows some suggestions to ensure the success of renewable energy systems from the community perspective. Further, figure 6.1 shows a possible model for sustainable rural electrification, taking into account most of the issues found in the literature. This model emphasises the importance of engaging the community and training them in the use of renewable energy. Also, the financial and political factors are taken into account to design a sustainability strategy to keep installed systems running in the long term.

Although the results of the surveys and interview studies are very much aligned, some discrepancy also occurs. In the studies carried out in Nepal and India, corruption was not identified as a pressing problem for electricity access or clean cooking. Not to mention problems of social order, including drug trafficking and threat of violence. These issues were not encountered anywhere in the visited regions of Nepal nor India, even though Arunachal Pradesh is known for growing and selling illegal opium. It seems that the level of organised crime do not compare among the three nations, making it a very specifically Colombian issue. On the other hand, obstacles such as gender inequality which was mentioned in the clean-cooking study, are both cultural and technology-related. This issue was absent in the energy needs surveys and the Colombia study. It is easy to see how cooking might be seen as more of a female affair than access to electricity. Even if having lighting in the evening can increase women's safety, electricity is a far more general concept that goes beyond gender.

Yet another example of discrepancy among the results of the above-mentioned studies is the role of technological issues when it comes to electricity access. While the Colombia study

Table 6.1: Suggestions to ensure sustainability of renewal energy projects[**Alvarez CIDET 2019**].

Suggestion	Description
`Local system manager`	A technologically savvy community member has to be assigned the task of maintenance of the renewable energy system. They have to be educated enough to troubleshoot problems either alone or remote guidance by an expert.
`Sustainability plan`	Successful projects need a long-term plan including productive use cases and how electricity could boost them. The plan needs to take into account strengthening of local economic activity.
`Maintenance plan`	A plan to maintain the system infrastructure has to be in place, including future improvements.
`Training`	In order for a system to be successful, locals must be trained in technical, commercial and administrative tasks related to the system. Training should not take place only once but whenever previously trained people are replaced.
`Payment plan`	To ensure the sustainability of an energy system, the consumers must pay for the service. The fees should be enough to cover the costs of maintenance and to create a sense of value for the system.

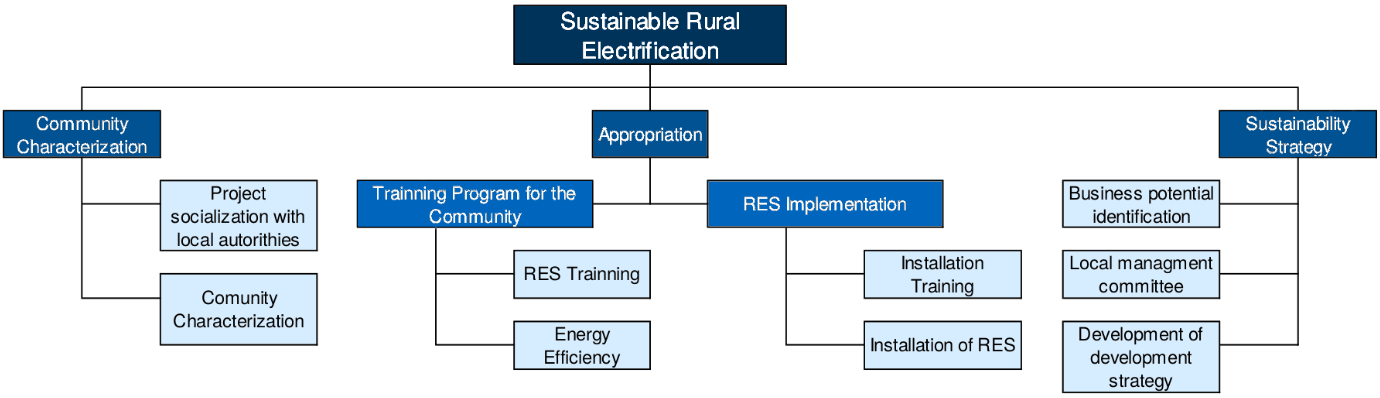


Figure 6.1: Sustainable renewable energy system implementation model[**Alvarez CIDET 2019**].

concluded that no technical issue hinders the advancement of renewable energies, the survey results from Nepal and India do show that power quality does play an important role in electricity access. This is why it was deemed meaningful to conduct a fifth study concentrating on power quality specifically.

The study on power quality in Nepalese off-grid systems found clear evidence of the power shortage mentioned in the surveys, and showcased substantial deviations from the national norms. Seeing the sustained power outages that routinely occur in the rural regions of Nepal, it becomes more understandable why some households are reluctant to pay for such services. As shown by the experiments conducted on common electrical appliances, the deviations in power quality translate directly into effects that consumers can see and feel, such as flickering lights, reducing illumination and increased cooking times when using induction cookers or electric kettles. Thus, technical issues should not completely be discarded even though they did not make it to the framework created as part of the Colombia study.

Based on the results of the studies on energy need as well as technical and non-technical barriers to renewable energy, it becomes clear that even though each approach offers new insight into the issue of planning and implementing sustainable renewable energy projects, none of them is all-encompassing on its own. Hence, when implementing a sustainable energy system project, the assessment of the location should include aspects of all three approaches. Conducting a ground-level survey of energy demand is absolutely essential to correctly design a system that fits the needs of the community without neglecting local traditions and the will of stakeholders active in the region. Further, including a barrier-based framework for the assessment is also necessary to identify and tackle issues before they become overpowering and halt the project altogether. Here either and adoption-based or stakeholder-based technique may be taken as described previously. And thirdly, as shown by the last of the discussed studies, ensuring sufficient power quality is an essential objective of a successful sustainable electrification project.

In part II, the focus is briefly shifted toward the technical solutions available to improve power quality, and the concept of load management is presented. Further, load management is explored in the form of two case studies, and their potential as means of improving the longlivedness and sustainability of small off-grid installations based on renewable energy is discussed.

Part III then goes on to propose, design and implement a sustainable energy system for a rural village, based on the findings of the results presented in earlier chapters.

Part II

Load management as a solution to bad power quality

Chapter 7

Load management as a means to improve power quality in off-grid systems

In part 1 of this thesis, multiple factors affecting the advancement of renewable energy systems in rural areas were identified and assessed. Additionally, suggestions were provided on how to take them into account during the design and implentation of such projects. Most of the barriers discovered in part 1 are socioeconomic or legislative in nature, but one factor is purely technical: Power quality.

In the survey studies conducted in Nepal and India, insufficient power supply and hence bad service quality were shown to hinder households from using more appliances, even in cases where said devices would directly benefit them in terms of shorter cooking times, improved health or increased hours of study. Further, bad service quality was shown to dissuade people from adopting electricity even in places where the connections are given free of charge and the national grid is available. In some parts of India, this has created a vicious cycle of households not paying for the poor-quality service, and the government or private electricity providers not having the incentive to improve it due to low revenues from the customers[10]. Circumstances such as this can effectively stall progress towards universal energy access.

In the last study presented in part I, power quality of off-grid installations was recorded and its effects on common appliances were analysed. It was shown that, beyond the obvious detrimental impact of power outages on consumer satisfaction, voltage deviations lead to longer cooking times, inefficient charging of battery-based appliances, and disturbances in lighting conditions. All of these can decrease households' appreciation for the electricity service provided.

In this part of the doctoral thesis, power quality in off-grid systems is examined as a control problem, and various load management algorithms are explored as a potential solution. Load management is a strategy used to match the power generated with that consumed by the loads present in an energy system. Actively matching supply and demand keeps the system's voltage level stable, and can improve the utilisation of energy. An example of the latter is automatically charging batteries when surplus power is available.

As mentioned previously, off-grid energy systems are more susceptible to power quality issues than regional or national grids, and this increases the need for effective and cheap load management solutions. In a rural context, a load management system needs to be simple so that communities can troubleshoot and maintain it irrespective of their level of education (obviously after proper training), and cheap enough not to substantially increase the already high investment costs of off-grid systems.

This chapter gives an introduction to energy-system control and discusses different strategies and topologies. Further, the hardware and software constraints posed by their application in a rural setting are discussed. Subsequently, in the next chapters, two load management algorithms are developed and compared to assess their suitability for rural implementations. The two methods are rule-based load management, and load management based on model-predictive control. The former is very simplistic but robust, and the latter allows for increased flexibility at the expense of higher computational requirements. In the following, the terms energy system and microgrid are used interchangeably and both refer to small off-grid installations.

7.1 Load management

The main tasks of a load management system[1] are to deliver stable power to consumers, and to improve the usage of resources within an energy system[76]. These goals are realised by controlling how much power is produced and where it is flowing to at a given time. As an example, if a sunny day is causing overproduction of solar power, optimally the load management system would use the excess power to charge batteries or heat water instead of directing it to a dump load or even disconnecting the solar panel. This way, the energy would not be wasted but stored for later use.

The simplest load management systems only switch power sources and loads on and off, whilst more complicated systems control the power output of each source, and the input of each sink. Further, there may be multiple layers of control that all work at different time steps. The architecture of the load management depends on its use case, with centralised and distributed options available.

Architecture and design

The Control methods of load management systems may be categorised based on their architecture, ranging from fully centralised to fully decentralised [77]. In conventional grids, i.e., those without renewable energy sources, control methods have traditionally been starkly centralised. In renewable microgrids, however, the power sources are typically of distributed nature and have different owners and objectives. In such cases, highly distributed control is justified and often necessary [77]. The following control categories in terms of architecture exist:

1. Centralised control

---

[1] Load management is often called energy or power management as well. The terms power management and load management differ mainly in the time scale of the control, where power management addresses voltage and current fluctuations ona microsecond level. Load management addresses phenomena with time constants from milliseconds to several seconds.

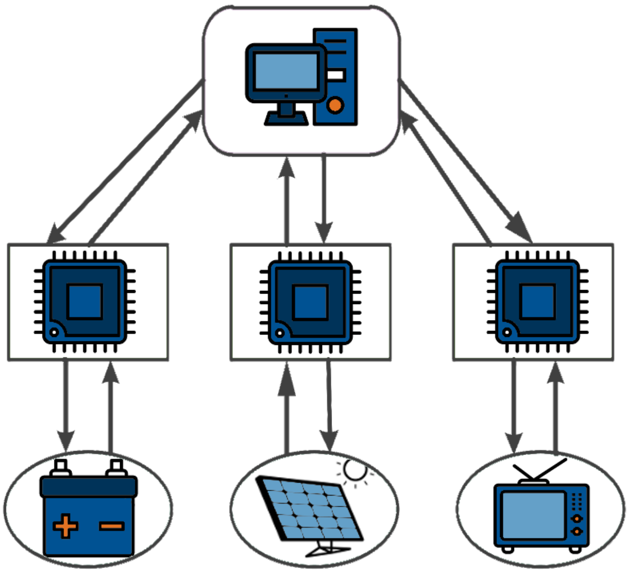


Figure 7.1: Centralised control scheme with one master controller that provides control signals to localised controllers. These in turn send control signals to the grid components[78].

2. Distributed control
3. Peer-to-peer control

In fully centralised control, a central controller determines all control actions within the energy system. All measurements from the grid components are sent to the central controller that then uses this information to decide what to do in the next time step. The presence of local controllers is optional, and they do not take part in deciding how much power should flow in or out of a component but merely control it to reach the goals given by the central controller. For example, the master controller could demand a certain power output from a solar panel, and the local controller would try to meet this goal by controlling the duty cycle of the power converter that connects the panel to the microgrid. Figure 7.1 shows an schematic of the centralised control architecture.

The advantage of centralised control is improved controllability due to the controller having perfect information. This means that all available information is sent to the controller so that it can take the best possible decision at each time step. Obvious disadvantages of this architecture include heavy computational burden on the central controller, the complex communication system needed to transfer information, and the single point of failure that this setup creates. If the central controller malfunctions, the operation of the whole energy system comes to a stop[78].

In distributed control, the central problem of balancing power supply and power demand is divided into multiple smaller ones, grouping components together in a microgrid. Each group has a central controller and optionally local controllers as well. If the original centralised problem was solved with an optimisation algorithm, this algorithm needs to be decomposed so that it can be solved iteratively by the group controllers. This is typically done with Lagrange

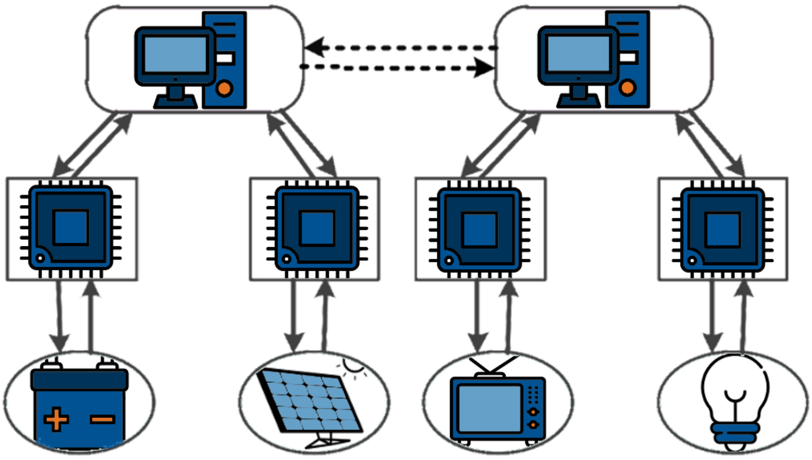


Figure 7.2: A distributed control architecture. Multiple high-level controllers exist that send control signals to their local controllers, and additionally exchange information with each other (dotted lines). The local controllers again control the components[78].

multipliers[77].

The distributed control architecture mitigates the problem of single point of failure by having more controllers but the hardware costs may increase. Decomposing the centralised control problem decreases the computational requirements but the communication system is potentially still rather complex. Figure 7.2 shows a possible distributed-control setup.

In peer-to-peer control, there is no central control unit, and the local controllers communicate with each other to spread information. The computational burden is greatly reduced, but this control paradigm often leads to compromised (pareto) optima. At best, plug-and-play operation is possible where components may be added or removed from the grid on the fly. There is no single point of failure, and hence one component's failure to operate will not affect the overall energy system. However, if all components in the system need all the available information, the communication system will be complex. Figure 7.3 shows how the peer-to-peer control architecture works.

As discussed above, the centralised and distributed control architectures may or may not include local controllers that take orders from the central units. In many cases these local controllers may not be considered part of the load management system. For example, a mobile charger has a inbuilt AC-DC converter with its own control circuit that provides the right amount of power to the battery of a mobile phone. The controller is present and has an effect on the energy system, but takes no part in its load management. the central controller can only disconnect it if it is using too much power, and reconnect it when excess supply becomes available. This is often the case with other components of a microgrid as well, especially if inverters and DC-DC converters are proprietary parts of each component. Including local controllers into the energy system allows for more flexible control but often requires more complex control algorithms, and higher expenses.

In general, a microgrid may comprise multiple levels of control, each operating at different time steps and pursuing different objectives. The lowest level is caller primary control, and happens

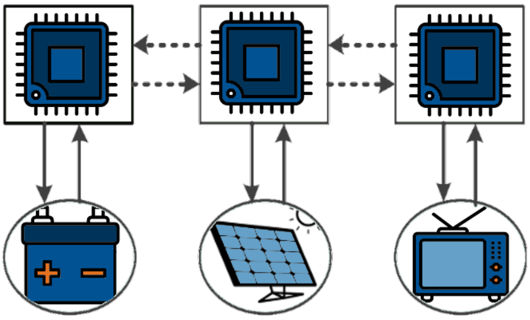


Figure 7.3: In a peer-to-peer control architecture, no centralised controller exist and the local controllers are responsible for the grid components' operation. Additionally, the local controllers exchange information with each other (dotted lines)[78].

at the level of the converters interfacing appliances, power sources and storage systems with the microgrid[79]. Primary control responds to system dynamics and transients, often at time steps in the range of milliseconds. Primary controllers can regulate converter voltage or current at the output or input side, and perform fault detection. Traditional one-directional converters usually have an outer voltage loop and an inner current loop PI(D) controllers.

Primary-level controllers may also perform power sharing. In centralised control architectures, master/slave power sharing control or concentrated control with a global synchronisation signal are traditionally utilised[79]. In master/slave control, one unit in the microgrid has to be chosen as the voltage source or grid-forming converter, and the other converters perform as current sources. When no communication methods between the converters are available, droop control may be utilised. This minimises the communication need and makes the system easily scalable.

The next level of control is where load management tasks are performed. This is called secondary control, and is usually responsible for the economical and reliable operation of an energy system[80]. The secondary controller optimises power flow and assigns set points for lower-level controllers if a two-way communication method exists. If not, the secondary controller is reduced to making switch-on and switch-off decisions as explained previously.

Load management is often realised as an optimisation problem. Then, the cost function usually consists of economic factors such as fuel cost, energy prices, startup costs, and reliability factors such as loss-of-load[81]. The requirements on the energy system's operation may be formulated as constraints of the optimisation problem, and range from the balance between supply and demand to energy storage capacity limits and maximum power ratings.

At its simplest, the load management layer analyses measurements taken at different points in the microgrid and acts upon this information. Recently, forecasting methods for load behaviour and weather conditions have been introduced to load management systems to optimise scheduling[81]. Especially in large-scale microgrids, machine-learning algorithms creating predictions are becoming commonplace. For small systems, predicting load behaviour is very complicated but as the number of consumers grows, the problem shifts from forecasting individuals to forecasting trends, which is easier. The same applies to weather forecasts in the sense that a small energy system will have fewer measurement locations. Hence it is affected by momentary events such as clouds of gusts of wind.

A third level of control may be used to coordinate neighbouring microgrids and distribution management systems. It is responsible of any energy trading between energy systems, and does not deal with power quality per se. This level is absent in off-grid energy systems[82].

Methods and algorithms

There are numerous approaches to load management in the literature, and this section gives an overview of the most common methods used in off-grid renewable energy systems. As the main task of a load management system is to balance supply and demand, the core concerns how to decide which generating units and loads to switch on at any given time[83]. This decision-making problem is often formulated as one of the following:

- an optimisation problem
- a rule-based problem
- a machine-learning problem

If treating the load management task as an optimisation issue, a multi-objective approach is often necessary[76]. The maximum usage of renewable sources should be achieved whilst minimising storage cycles and trying to meet consumer demand. Depending on operating conditions, many objectives might compete with each other, increasing the complexity of the optimisation problem. At the same time, constraints set by generation capacity, current and voltage limits etc., need to be taken into account. The uncertainty of renewable energy sources adds to the complexity of the optimisation problem that still needs to be solved under real-time requirements.

There are examples of linear-programming-based load management[84] but due to the complexity of renewable energy systems, this often involves stark simplifications and linearisation of the underlying microgrid model. The trend in optimisation is towards more complex methods involving genetic algorithms, and mixed-integer or non-linear optimisation[83] The advantage of genetic algorithms and swarm-based optimisation is that they allow for complex formulations, are acceptive of multi-criterion problems, and always diverge to a solution, ensuring improved robustness[85] as opposed to classical iterative optimisation[86]. However, no guarantee of the optimality of the found solution exists. Further, these methods are very computationally expensive and the unpredictable outcome of the optimisation. These algorithms in general are not deterministic and as such, do not lead to the same solution if used multiple times on the same starting conditions.

Non-linear optimisation, and especially quadratic optimisation algorithms are very popular in microgrid management systems[83]. The decision making within load management often include discrete as well as continuous control variables, and hence the optimisation problems are of mixed-integer nature. Off-the-shelf software packages such as GAMS and CPLEX make solving such problems straight-forward, but computational time grows quickly as the problems scale. Mixed-integer (non-)linear (MILP or MINLP) optimisation has traditionally been solved centrally but decomposition schemes exist that allow for distributed solving[]. One further advantage of MI(N)LP algorithms is that they are deterministic which greatly simplifies their design and testing.

Rule-based systems, as the name implies, relies on a set of rules in order to take decisions within the load management system[81]. At its simplest, this could mean setting constant upper and lower limits for power generation and consumption, and connecting or disconnecting components that cannot stay within these limits. In this case, no model of the energy system is needed, and the computational requirements are very low. The disadvantage of such a simple algorithm is that there is no guarantee that the given set of rules would lead to optimal operation. More elaborate methods may include an optimisation step, and use the optimisation result to formulate rules. Fuzzy logic may also be used.

If treating load management as a machine-learning problem, no model of the physical system is needed. The loda management systems can be based on neural networks, decision trees or other models, and is trained to land at the right decision under any circumstances by feeding it past data of the surrounding conditions and operational values[81]. Numerous training methods exist ranging from supervised to unsupervised and reinforcement learning. How to take decisions within a loda management system is usually only part of the control. An actual control framework with a centralised or decentralised architecture is often needed to act upon the results of the decision-making system. Classical centralised architectures favour optimisation-based decision making as the central controller has enough computational power to reach optimal results and act upon the in acceptable time. Some popular control methods include predictive control and fuzzy control[87][88]. In predictive control, or model predictive control, a dynamic model of the energy system is used to estimate its future behaviour. Based on the estimate, control signals are modified. The optimisation of the predictive control may be realised with any of the aforementioned schemes, and for the future predictions, classical estimation methods such as the Kalman filter may be applied[89]. In fuzzy control, discrete values are fuzzyfied into continuous ones[86]. Fuzzy logic has an advantage when multiple parameters and objectives exists, and no one configuration is definitely the optimal.

In peer-to-peer architectures, each node can make their own decisions without taking other units into account, but even then communication usually has some effect on the decision-making. Some popular methods for peer-to-peer control are multi-agent systems (MAS), distributed model predictive control (DMPC), consensus-based techniques and decomposition methods[83]. MAS are autonomously acting computational units that are motivated in their actions by a given goal. They try to reach their goal but simultaneously react to the actions of the other agents around them. The MAS framework has a bottom-up structure that leads to system-wide phenomena, reaching a solution that is usually pareto optimal[76].

DMPC is similar to classical MPC but the centralised optimisation problem is broken down into smaller ones and solved locally. The local solution are then combined in an iterative process to reach a global solution.

The choice of decision-making algorithm and control framework depends heavily on the energy system and its implementation constraints. If enough computational resources are available, sophisticated algorithms utilising machine learning or artificial intelligence may provide good results. For a limited budget, simpler methods have to be considered. In the next section, some of the constraints applicable for rural electrification and small off-grid energy systems are discussed, and two suggestions for a possible control system are made.

7.2 Design criteria for a load management systems for rural off-grid installations

As seen in part 1 of this thesis, insufficient power quality is the main technical barrier to increasing the share of renewables in rural electrification. Local communities in Nepal and India were shown to be willing and able to pay for more electricity but pushed back by the bad service. In other cases, the initial bad experiences with power suppliers had dissuaded many households from paying their monthly fee, causing the supplying companies to lose interest in improving the service.

Based on the above findings, it is clear that improving the power quality is essential in ensuring the success and long-livedness of a renewable energy system in rural low-income regions. A load management system could do just that. However, adding new hardware to a system that already faces the problem of high capital cost could be detrimental to any rural electrification project. Other requirements on the load management system have to do with robustness and safety, as most people in the target communities are unlikely to have the technical capability to troubleshoot hardware or software issues, nor to handle the hardware in a safe way without training.

To ensure that a load management system is created with the rural application in mind, some general criteria have to be set, and subsequently followed from design to implementation. Further, requirements need to be set not only for hardware but for software as well. In the following the main design criteria are described in detail.

7.2.1 Hardware constraints

As mentioned before, any additions to the energy system should not increase the capital cost of the energy system dramatically. In the best-case scenario, the added cost of load management would be just a few per cent of the original investment. Additionally, in order to justify the extra spending, the load management system is expected to significantly improve the power quality of the energy system, and to ensure that the power is shared equally between all consumers. This requirement stems from the findings of the survey conducted in Nepal, where it was found that for the same monthly fee, some families were able to plug in several devices, and some only a few light bulbs. Such lack of oversight and regulation is discriminative and can lead to dissatisfaction.

Given the challenging geography of many rural areas, and the evident lack of infrastructure, maintenance costs of off-grid energy systems can be high. Thus, it is understandable that the implemented load management system should either be very easy to maintain and repair with cheap local materials, or robust enough to be maintenance free under normal circumstances. In the best-case scenario, the system's hardware would be not only robust and log-lived, but also user friendly and easy to repair.

Further aspects essential for the sustainability of the load management system is its scalability. It should be flexible enough to easily accommodate new components into the energy system, and especially new connections as people move into the community and wish to be connected as well. To make scaling up easier, the hardware components needed should be easily accessible and no modification of the software should be necessary. A further restriction to the hardware is that it should not use a low of power to operate. In the rural context, the energy systems typically deliver only a few hundred watts to each household, and the load management system should operate clearly below that in order to take supply away from the consumers themselves.

7.2.2 Software constraints

The afore-mentioned hardware criteria logically impose constraints on the software design as well. The price of the hardware directly transfers to the amount of available computational power and memory usage in the proposed load management system, and can have significant restrictions on the algorithm used. Also, due to the application's power quality goals, the algorithm must be capable of operating under hard real-time constraints. The load management algorithm has to react without delay to events within the energy system, even in cases where an "optimal" operating point may not be reached.

The robustness of the hardware implies that there is no malfunction in either the physical system or the software under any circumstances that may occur in normal operation. This means that all possible fault scenarios and use case should be caught and dealt with within the software. User friendliness should be taken into account by minimising the need of user intervention during operation. If scaling up without changing the software is impossible, at least it should be possible without rendering the whole energy system non-operational for extended periods of time. Table 7.1 summarises the hardware and software requirements for a sustainable load management system.

Based on these requirements, which load management method should be used in rural electrification projects? Is there one method that stands out amongst all others? Unfortunately, the choice is not universal, and depends on many aspects of the project, ranging from budget to available infrastructure and the technical know-how of the locals. However, some methods can directly be ruled out as unsuitable. Among these are any methods based on artificial intelligence or machine learning, simply due to their extensive computational requirements. The decision is a lot harder between optimisation techniques and a rule-based representation. Another thing to consider is whether or not the control should be centralised or decentralised. Further, the modelling detail should also be decided upon, as too simplistic approaches may lead to unsatisfying results, whereas taking the modelling tot far will only increase the computational burden without improving the results.

To explore different options for load management strategies, two case studies were created. One with distributed control architecture utilising a very simple rule-based algorithm without an underlying physical model, and the other a centralised load management scheme relying on mixed-integer quadratic optimisation and model predictive control. In the remaining of part II, both of these case studies are presented in detail and tested. Finally, the are compared with the requirements laid out in this chapter, and a decision is made on which is the most suitable to control a small renewable energy system.

Table 7.1: The hardware and software requirements for load management systems in the rural electrification context.

Type	Requirement	Description
`Hardware`	cheapness	little added capital and maintenance cost
`Hardware`	efficiency	significant improvement in power quality
`Hardware`	robustness	long lifetime and little maintenance
`Hardware`	easy maintenance	spare parts easily available and easy to install
`Hardware`	user-friendliness	little user intervention needed
`Hardware`	low power needs	the hardware cannot consume significant power meant for users
`Software`	low computational needs	no complex algorithms
`Software`	real-time capability	always deliver results without delay
`Software`	robustness	all usage scenarios dealt with within the algorithm
`Software`	user-friendliness	no user input needed
`Software`	scalability	easy to add components without altering the algorithm

Chapter 8

Case study I: Distributed rule-based load management system

This case study looks at a distributed load management system based on a simple rule-based scheme. The approach is non-invasive in the sense that it does not affect or communicate with the local controllers[1] of any energy system component directly. This allows for off-the-shelf battery chargers, inverters and ups's to be used, and only high-level decisions are taken on which component should be connected to the grid at any given point in time.

A simple rule-based load management system works without a mathematical model, and relies solely on power measurements and hard-coded minimum and maximum limits for its operation. The resulting decrease in system complexity makes the algorithm light-weight at the cost of potentially delivering suboptimal control inputs.

When designing the rule-based load management system, no assumptions were made about the grid nor the characteristics of the energy sources. Local controllers were given the power to control and limit the power flowing in and out of the components, and the rule-based system acted on a higher level connecting and disconnecting units through switches. The design was realised keeping in mind safety, robustness and system cost, with the aim of meeting the requirements posed in chapter 7. The simplicity of the control system was also a design aim. The system was verified on the open-source platform Arduino UNO for the main controller, and Arduino Leonardo for the auxiliary controller, of which several were needed to create the distributed control system.

8.1 Load management algorithm

In this case study, a renewable energy system to consist of a AC bus, battery storage, a photovoltaic generator, and a micro-hydro turbine. Three types of load were included into the design. The first type is a high-priority continuous load that needs to be powered throughout the day. This could be a hospital, a school or another public space within a community. In the considered power system, there are two lines of the high-priority type. The second type is a load that receives power in the evenings, which could correspond to the households of a village.

---

[1] Local or secondary controllers are the inverters, charge controllers etc. within an energy system. See chapter 7.

This decision was taken based on the survey results in Nepal and India (see section 3.2.2). Most villagers reportedly spend their days at work and need no electricity until sundown when they return. The final load type is for outside lighting that would turn on at sundown and stay on late into the night, allowing villagers to walk around safely after dark.

The controller architecture is distributed with one main controller and several auxiliary controllers that exchange information directly. The auxiliary controllers are not slaves to the main controller and realise their control tasks independently. An additional unit takes care of logging generation and consumption within the microgrid.

The main controller is directly responsible for the high-priority load switches as well as for outside lighting, but it can also cut off the household power in case the total supply cannot cover the hard-coded maximum demand. In order to make this decision, the power input of the hydro turbine and the PV plant are measured. Also, if the voltage of the hydro turbine drops too low, loads of lower priority rating are dropped. Figure 8.1 shows the logic of the main controller. It measures the input voltage of the PV inverter and the hydro turbine after half-wave rectifying the AC signals. The inverter voltage is used to calculate the active power consumption and the power factor in the microgrid, and the hydro turbine voltage is monitored to detect system overload in case the bus voltage drops too far from the nominal $230V$. If this is the case, the neither outside lighting nor the households will receive power.

The RMS voltage measurement is computed from the half-wave rectified signal by recording an average of the peak voltage value v_{pk} over 160 cycles, and using the below equation:

$$v_{RMS} = M\left(\left[2v_{pk}\frac{1}{\sqrt{2}}\right] + v_{diode}\right), \tag{8.1}$$

where M is the transformation ration of a step-down transformer, and v_{diode} is the forward voltage drop of the rectification diode. The RMS current may be measured directly with a shunt resistor, or indirectly with a Hall sensor. The former relies on Ohm's law, whereas the latter makes use of Faraday's and Ampere's laws. The advantage of indirect current sensing is the galvanic isolation between the power system and the measurement circuitry. The RMS current measurement is discussed in more detail in section 8.3.

The power factor PF is computed from the measured RMS and instantaneous values as follows:

$$PF = \frac{P}{S}, \tag{8.2}$$

where P is the active power:

$$P = v_{RMS} i_{RMS} \tag{8.3}$$

and S is the apparent power:

$$S = \frac{1}{N}\sum Ni\left(v_i i_i\right). \tag{8.4}$$

Above, v_i and i_i represent instantaneous voltage and current measurements, and N is the number of samples.

The auxiliary controllers provide power to the second load type which represents households. They make sure that the households keep to their maximum allowed power, and cut off electricity for 30 seconds if the limit is crossed. Figure 8.2 shows the logic of the auxiliary controllers. They are powered by the main controller and are only operational between 17:00 and 23:00.

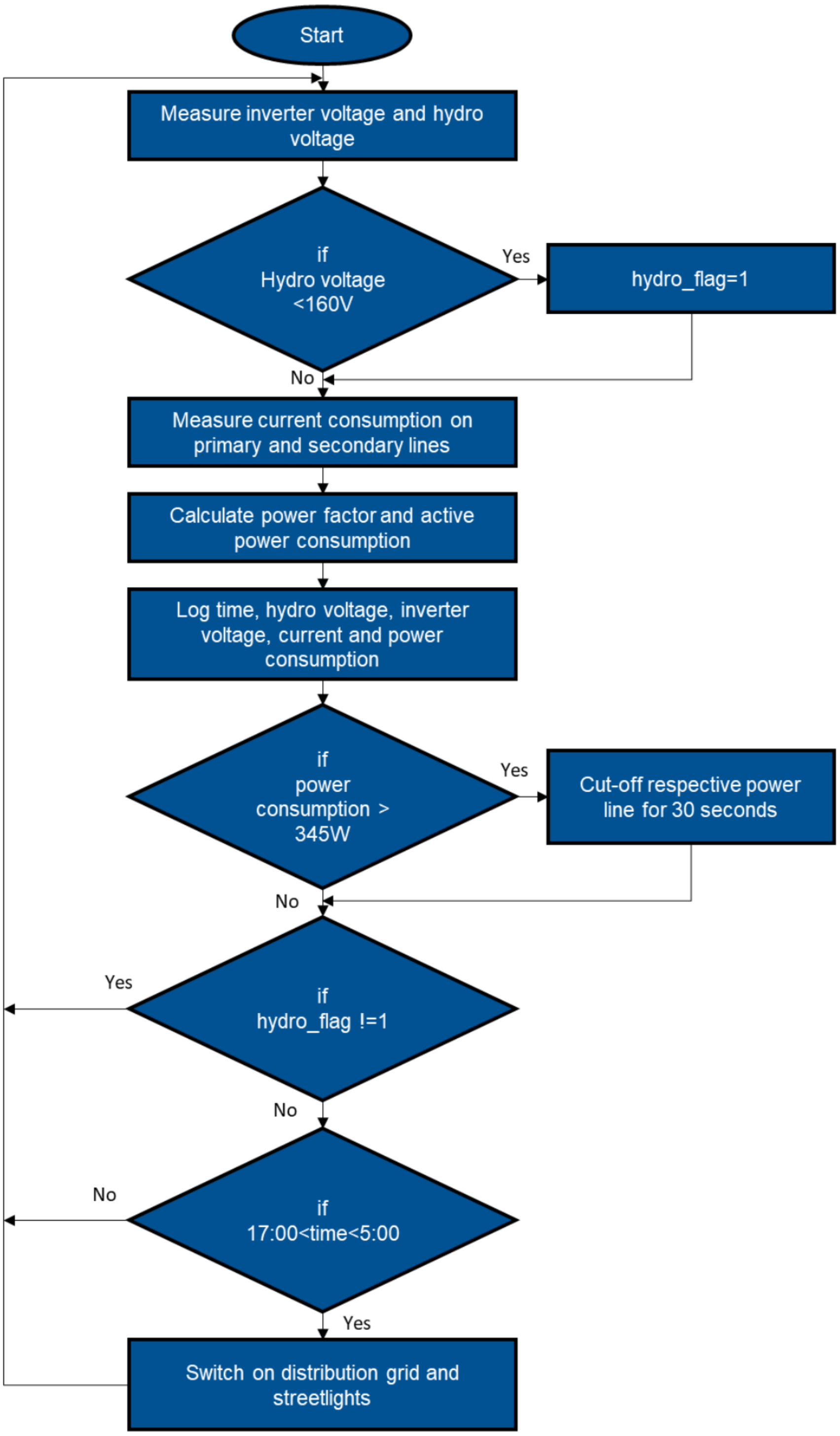


Figure 8.1: Logical flow chart of the main controller[90].

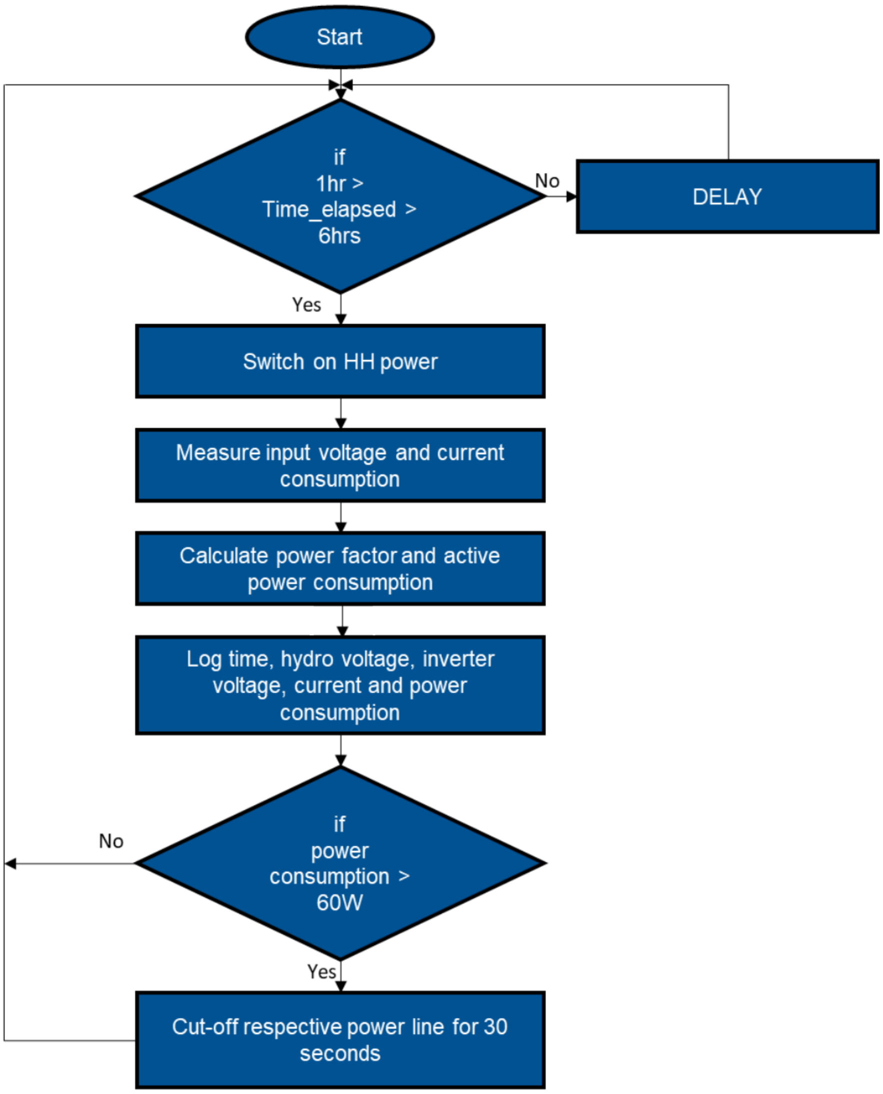


Figure 8.2: Logical flow chart of the auxiliary controller[90].

Once powered on, the auxiliary controllers measure the input voltage of the distribution system after half-wave rectification, and monitor the current flowing to each individual household. The measurements are then used to compute the active power consumption and the power factor for each household.

8.2 Test scenario

For the testing of the rule-based load management system, a scenario of a renewable energy system was created based on the survey results obtained from Uttar Pradesh and Arunachal Pradesh (see section 3.2.1). The system consists of a 1.3 kW PV installation, a 1 kW micro-hydro turbine, and a 400 Ah battery bank. As explained before, three types of load are present, namely high-priority loads powered continuously, outside lighting load which is turned on

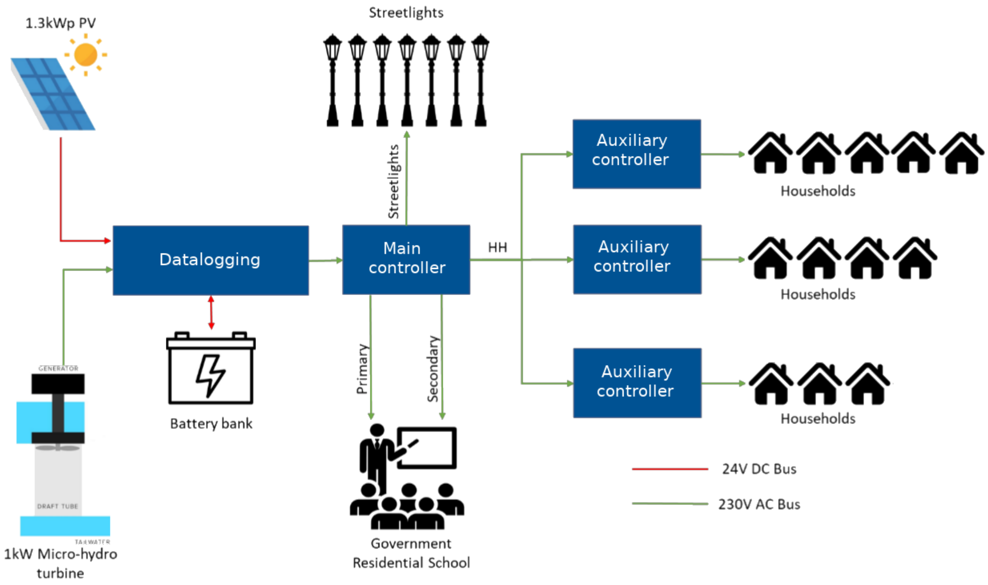


Figure 8.3: Schematic of the considered microgrid[90].

between 17:00 and 23:00 every day, and finally the household load powered between 16:00 and 23:00. The high-priority load corresponds to a public facility such as hospital or school that needs to operate around the clock. Villagers are routinely at work from early in the morning to late in the evening, which justifies the power connection only being granted in the evening hours. Part III shows that these conditions are similar to the actual implementation of the pilot sustainable energy system. Figure 8.3 shows a schematic of the considered microgrid layout. As shown in the microgrid schematic, the high-priority load (denoted "Government residential school" in the schematic) is divided to two lines. Both lines are restricted to $345W$ each, and the power is cut off for 30 seconds in the respective line in case this limit is exceeded.

Twelve households were considered to be part of the microgrid, and hence 12 household lines were defined for the case study. Each line receives a constant $60W$ power supply between 18:00 and 23:00. The Arduino Leonardo platform has a limited number of output pins which controls how many lines may be managed by one unit, and therefore a total of three Arduino Leonardos were needed to control the power flow of 12 load lines.

In a simple rule-based system, the most important part for the successful functionality of the algorithm is that the measurements are accurate. Hence, the testing of the load management system centered around connecting various load types to verify the controller behaviour. The measurement precision and the calculations for power factor and active power consumption were also examined. The measurement error was identified by using multimeters and comparing their results to those received from the Arduino-based load management system. The relative error was simply computed suing the following equation:

$$error\% = \frac{i_{ref} - i_{arduino}}{i_{ref}} \times 100\% \tag{8.5}$$

The controllers were tested with lighting loads, resistive loads and loads containing power electronics, which is in accordance with the studies carried out in Nepal and India, where

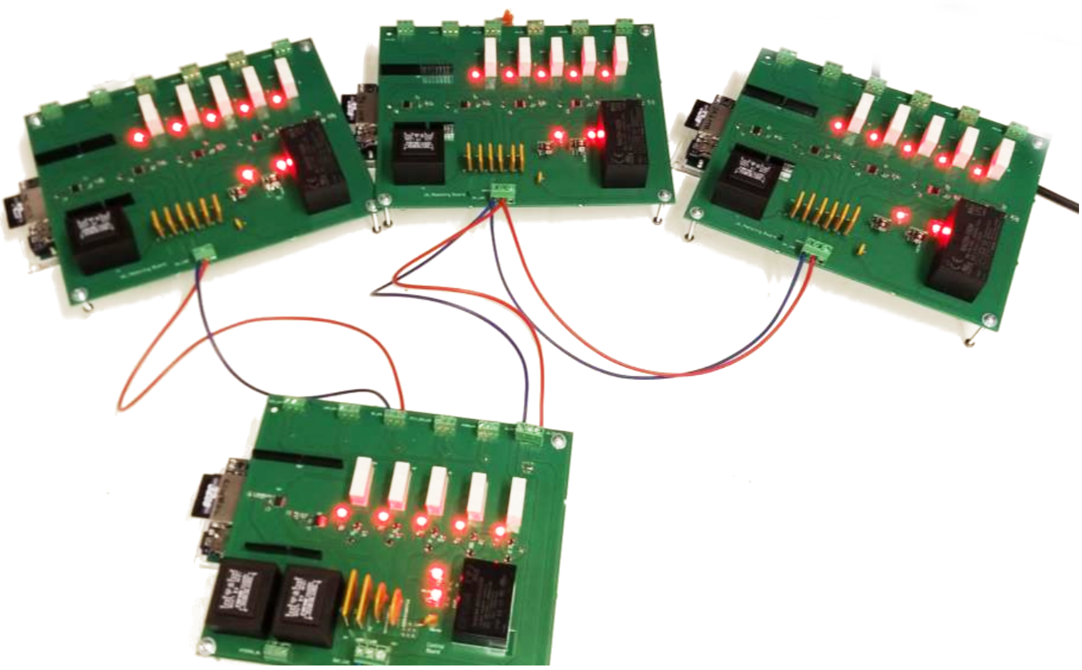


Figure 8.4: Test setup of rule-based load management system[90].

appliances commonly used in rural households were identified. Figure 8.4 shows the test setup with the main and auxiliary controllers.

8.3 Implementation

The main was implemented on the Arduino UNO microcontroller that carries the ATmega328p chip. It has 32 kB of programme memory and 2 kB of SRAM, which greatly restricts the complexity of the software that can be run on it. Additionally, the auxiliary controllers and the datalogger functionality were implemented on Arduino Leonardos which has the ATmega32u4 chip, with similar specifications to ATmega328p.

The voltages in the microgrid are measured by means of a step-down transformer and a half-wave rectifier circuit. The signals are sent directly to the Arduinos' analog-to-digital (ADC) converters, and an external voltage reference of $3.3V$ is used for added accuracy. This means that the input range for signals is $0 - 3.3V$, and thus a transformation ratio of $M = 230 : 3$ is used. The half-wave rectifiers are needed because the Arduinos can only withstand positive input voltages. Figure 8.5 shows the voltage sensing circuit used on all the Arduinos.

The current measurements on the main controller side has a maximum of $1.5A$ RMS, which is a direct result of the operating limit of $345W$ per line at $230V$. To measure this current, a Hall sensor was chosen, with a sensitivity range as close as possible to the normal operating conditions, and with the capability of measuring bidirectional currents. The chosen chip is ACS723-05. It is a 8-pin $\pm 5A$ sensor with a sensitivity of $400mV/A$. The output of the current measurement is given in volts, and measured by the Arduino UNO/Leonardo microcontroller.

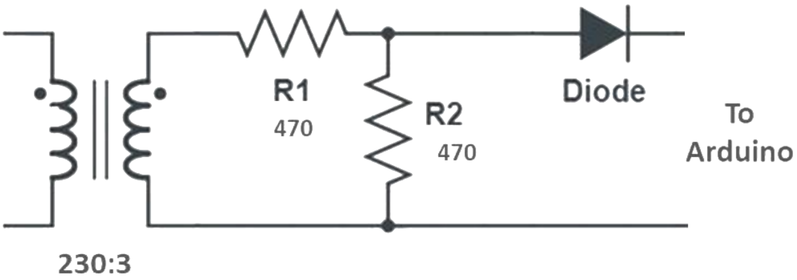


Figure 8.5: Voltage sensing circuit[90].

The RMS current is then calculated as

$$i_{RMS} = \frac{\sqrt{\frac{v_{tot}}{N}}\, i}{C_{sensitivity}}, \tag{8.6}$$

where v_{tot} is the sum of squared instantaneous values, and N is the number of stored sampler. $C_{sensitivity}$ is the sensitivity of the sensor. The instantaneous values are measured over 160 cycles.

In the auxiliary controller, current is measured with shunt resistors. The maximum value of current on each household line under normal operating conditions is $261mA$ RMS, and a standard 1Ω shunt resistor was chosen as the sensing element. This corresponds to a voltage drop of $0.37V$, and a gain difference amplifier is needed to accurately sense the current on the Arduino platform. The voltage measured by Arduino is again transformed into the current value. For the shunt resistor, the computation takes the following form:

$$i_{RMS} = \sqrt{\frac{v_{tot}}{N}} \tag{8.7}$$

8.4 Results

The controllers were tested in the presence of different types of load. The maximum relative error was found to be 5.2 per cent, which is fairly accurate for such a low-cost setup. In case of lighting loads (incandescent, CFL and LED), the maximum error was -2.2 per cent, with the measurement being the most accurate when testing LEDs. The resistive load consisting of a rice cooker saw the greatest error (5.2 per cent), and the electronic loads induced a maximum relative error of 2.4 per cent. A LED TV sent and a set-top box were tested in this last category. In the remainder of this section, a selection of results of the test are shown in tabular form.

Lighting loads

Incandescent bulbs, CFL bulbs and LED light were all tested to make sure that the measurements and calculations carried out within the load management system are accurate. Table 8.1 shows the results for a 9W LED bulb with a manufacturer-specified power factor of 0.60. The power factor calculated by the controller was somewhat lower, leading to an active current of $35.52 - 36.26mA$. The reference current was measured to be $35.98mA$, leading to a relative error of -1.07 per cent.

Table 8.1: Accuracy results for 9W LED bulb.

voltage (V)	apparent current (mA)	power factor	active current (mA)	active power (W)
232.70	66.93	0.54	36.17	8.42
232.26	64.44	0.56	36.26	8.42
231.61	63.45	0.57	36.04	8.35
232.26	63.72	0.57	36.19	8.41
232.04	63.68	0.56	36.04	8.36
232.04	63.85	0.56	36.03	8.36
232.04	63.74	0.56	35.92	8.34
231.83	63.79	0.56	35.99	8.34
232.04	63.71	0.56	35.67	8.28
232.04	63.53	0.56	35.52	8.24

Table 8.2: Accuracy results for 660W rice cooker.

voltage (V)	apparent current (mA)	power factor	active current (mA)	active power (W)
226.82	2998.51	0.97	2893.86	656.39
227.05	2998.32	0.97	2894.28	657.14
227.05	2992.34	0.96	2887.31	655.57
227.52	2991.25	0.97	2886.56	656.71
227.28	2989.64	0.96	2882.91	655.25
227.75	3001.52	0.97	2899.77	660.43
227.98	3016.47	0.96	2911.50	663.76
227.67	3015.03	0.97	2908.00	664.96
228.67	3016.78	0.97	2911.49	666.41

Resistive loads

To test the load management system's accuracy with purely resistive loads, a 660W rice cooker was tested. The active current measured by the multimeter was $3.06A$ whereas that measured by the Arduinos was between $28.83 - 30.13A$. Taking the average current measured, the relative error came up to 5.22 per cent. The power factor of purely resistive loads should be equal to one but the measurement system calculated a value of 0.97.

Electronic loads

To test loads containing power electronics, an LED-powered TV set and a $18W$ set top box were tested. The current on the latter was $27.1mA$ according to the reference whilst the measurement system recorded an average value of $26.67mA$, leading to a relative error of 1.59 per cent. The power factor was not given by the manufacturer but could be seen to lie around 0.5. Additionally, the functionality of the switching relays were tested by increasing power demand, on the household lines to over $60W$, and to over $345W$ on the high-priority lines. The system reacted as expected.

Table 8.3: Accuracy results for 18W set top box.

voltage (V)	apparent current (mA)	power factor	active current (mA)	active power (W)
233.35	37.24	0.49	18.40	4.29
233.14	42.88	0.50	21.47	5.01
233.79	53.35	0.52	27.59	6.45
233.35	52.84	0.52	27.49	6.41
233.79	53.35	0.52	27.84	6.51
233.79	55.08	0.52	28.74	6.72
234.01	55.10	0.52	28.75	6.73
234.01	55.24	0.52	28.80	6.74
234.01	54.97	0.52	28.80	6.74
234.01	55.09	0.52	28.84	6.75

Chapter 9

Case study II: Centralised load management system with model-predictive control

This case study examines a centralised load management system based on model-predictive control (MPC). MPC uses a state-space dynamic model to predict the future behaviour of a system, and optimises a given objective function over a set of input variables. The method naturally handles constraints, and has a closed-loop character. The formulation of multi-objective problems within the MPC framework is straightforward, and decision variables may be incorporated with few adjustments.

Despite their popularity in the literature, few MPC algorithms have been tested in real-time environments or on embedded platforms. Further, the majority of algorithms find application in grid-connected microgrids or in the presence of conventional generators. This leads to the assumption of a stiff grid that greatly simplifies the load management problem[91]. This further motivates why the applicability of MPC for small off-grid installations should be investigated.

The load management system examined in this case study assumes nothing about the type of the power sources within a RES, and does not rely on grid stiffness to realise the control task. At each time step, future power generation and load are predicted, and the optimisation constraints are updated accordingly. In case of power shortage within the microgrid, low-priority loads may be shed by opening circuit breakers. The design was realised with special attention on safety, real-time constraints and system cost, to meet the requirements posed in chapter 7, with the hope of obtaining an efficient algorithm with low CPU requirements. The performance of the PMS was verified on the open-source platform Arduino MEGA.

9.1 Load management algorithm

In this case study, a renewable energy system was assumed to consist of a DC bus, battery storage, centralised photovoltaic generator, and two types of load, namely high-priority and low-priority. The power output of the battery and PV systems were taken as the control inputs, along with the circuit breakers of the loads. The RES was modelled as a mixed logic dynamical (MLD) system, allowing for the representation of circuit breakers as binary variables $z_i \in 0, 1$.

Hence, a mixed-integer programming approach was necessary to solve for the optimal input. Considering the real-time and efficiency requirements of the embedded platform, a specialised solver was developed to solve the constrained mixed-integer quadratic problem (MIQP). A branch-and-bound method was used in combination with Hildreth's quadratic programming procedure. The latter is a dual active-set method based on Lagrange multipliers, and greatly simplifies the optimisation task.

Model-predictive control

A discrete model-predictive control (MPC) method was studied, and the battery state of charge (SOC) was chosen as the state x_m of the system. An augmented state-space model with embedded integrator was chosen to represent the dynamics of the renewable energy system, resulting in the following formulation:

$$\bar{x}_{k+1} = A\bar{x}_k + \begin{bmatrix} B_u B_{zk} \end{bmatrix} \begin{bmatrix} \Delta u_k \\ \bar{z}_k \end{bmatrix} + W_k \bar{z}_{k-1} \tag{9.1}$$

$$y_{k+1} = x_{m_{k+1}} \tag{9.2}$$

where $\bar{x}_{k+1} = \begin{bmatrix} \Delta x_{m_{k+1}} y_{k+1} \end{bmatrix}^T$, Δu_k is the PV power, and $\bar{z}_k$ represents the load switches. From Kirchhoff's current law, the power supplied by the battery is obtained implicitly from the PV and load powers. Thus, the number of optimisation variables is reduced, allowing for more efficient computation, leading to the following system matrices:

$$A = \begin{bmatrix} 10 \\ 11 \end{bmatrix}, B_u = \frac{\Delta t}{v_{bus}Q} \begin{bmatrix} 1 \\ 1 \end{bmatrix}, B_{zk} = \frac{\Delta t}{v_{bus}Q} \begin{bmatrix} P_{l1k} P_{l2k} \\ P_{l1k} P_{l2k} \end{bmatrix}, W_k = -B_{zk-1}, \tag{9.3}$$

where Δt is the discretisation time step, Q is the battery capacity, v_{bus} is the bus voltage, and P_{lik} is the load power for $i \in 1, 2$.
For each time step, MPC optimises a given objective function over a prediction horizon, subject to operational constraints. It is crucial to predict the behaviour of the system state, the load and the available PV power within the prediction horizon to correctly set the control input. Here, a Kalman filter was employed for state prediction, whilst power predictions were assumed perfect. The prediction horizon consists of N_p steps, and the optimisation is done for a control horizon of N_c steps. Traditionally, only the first step of the optimised input trajectory is used for the actual control[89].
The trajectory of the output over N_p, predicted at time step k, may be expressed as:

$$\bar{Y}_k = \begin{bmatrix} y_{k+1|k} \\ \dots \\ y_{k+Np|k} \end{bmatrix} = \Gamma \bar{x}_k + \phi_{zk} \Delta \bar{U}_{zk} + \Pi_k \bar{Z}_{k-1} \tag{9.4}$$

where $(k+1|k)$ denotes the prediction of a variable at time step k, and $\Delta \bar{U}_{zk}$ is the future control input trajectory of the form:

$$\bar{U}_{zk} = \begin{bmatrix} \bar{U}_k \\ \bar{Z}_k \end{bmatrix} = \begin{bmatrix} \Delta u_k \dots \Delta u_{k+Nc-1} \bar{z}_k^T \dots \bar{z}_{k+Nc-1}^T \end{bmatrix}^T. \tag{9.5}$$

Further, $\bar{U}_{zmax}$ contains the values:

$$\bar{U}_{zmax} = \left[u_{max} - u_{k-1} \ldots u_{max} - u_{k+Nc-2} 1 \ldots 1\right]^T \tag{9.6}$$

The objective function of the MPC algorithm was formulated as a quadratic equation as follows:

$$J_k = (\bar{Y}_{max} - \bar{Y}_k)^T(\bar{Y}_{max} - \bar{Y}_k) + (\bar{U}_{zmax} - \Delta\bar{U}_{zk})^T(\bar{U}_{zmax} - \Delta\bar{U}_{zk}) = \frac{1}{2}\Delta\bar{U}_{zk}{}^T E_k \Delta\bar{U}_{zk} + \Delta\bar{U}_{zk} F_k + G_k. \tag{9.7}$$

Thus, loss of load, and deviations from maximum SOC and PV operating point are penalised. The product of a transposed matrix with the original (i.e., $A^T A$) is always symmetric and square, and thus at least positive semidefinite. The cost function in equation (9.7) is hence a sum of two positive-semidefinite matrices, and preserves this quality. This leads to an invertible Hessian that lets one directly obtain an unconstrained solution for the MPC problem:

$$\Delta\bar{U}_{zk}{}^* = -E_k{}^{-1} F_k. \tag{9.8}$$

The following linear inequality constraints limit the feasible set of control inputs to those that are within the operating limits of the RES components:

$$SOC_{min} \leq SOC_k \leq SOC_{max}, 0 \leq P_{sk} \leq P_{smax}, P_{bmin} \leq P_{bk} \leq P_{bmax}, 0 \leq z_{ik} \leq 1, \tag{9.9}$$

where P_s is the PV power generation, and P_b that of the battery. In general, the constraints can be brought to a more convenient matrix form:

$$M_k \Delta\bar{U}_{zk} \leq \bar{\nu}_k. \tag{9.10}$$

All power sources are treated as controllable (renewable sources are controllable via an MPPT algorithm, and their Pmax is updated at every time step based on generation prediction).

Hildreth's quadratic programming procedure

Hildreth's quadratic programming procedure is an active dual method, the solution of which is based on using the Lagrange multiplier $\bar{\lambda}$ as the decision variable [89]. The dual problem may be written as:

$$\max_{\bar{\lambda} \geq 0} \left(-\frac{1}{2}\bar{\lambda}^T H \bar{\lambda} - \bar{\lambda}^T \bar{I} - \frac{1}{2} F^T E^{-1} F \right), \tag{9.11}$$

where $\bar{\lambda} \geq 0$ means that each element of $\bar{\lambda}$ is greater than or equal to zero. For the sake of simplicity, the time step k is dropped from equation (9.11) and subsequent equations, but the variables are all time-varying. The matrices H and $\bar{I}$ are defined as:

$$H = ME^{-1}M^T, \bar{I} = \bar{nu} + ME^{-1}F. \tag{9.12}$$

Hildreth's procedure is an iterative method, and cycles through the elements in $\bar{\lambda}$. The elements are adjusted either until $\bar{\lambda}$ has converged or until a specified number of iterations has been reached. The procedure may be expressed as follows:

$$\lambda_i{}^{m+1} = max(0, w_i{}^{m+1}), \tag{9.13}$$

with

$$w_i^{m+1} - \frac{1}{h_{ii}} \left(l_i + \sum_{j=1}^{i-1} h_{ij} \lambda_j{}^{m+1} + \sum_{j=i+1}^{n} h_{ij} \lambda_j{}^{m} \right) , \tag{9.14}$$

where m is the current iteration, and n the number of elements in λ. Variable h_{ij} is the ijth element of H. Due to its iterative nature, Hildreth's procedure is very reliable in real-time implementations [89]. Even with conflicting constraints, the method delivers a compromised sub-optimal solution without numerical instability. The final converged value of $\bar{\lambda}$ is denoted $\bar{\lambda}^*$, and the result of the primal problem is:

$$\Delta \bar{U}_{zk}{}^* = -E^{-1} \left(F + M^T \bar{\lambda}^* \right) . \tag{9.15}$$

Mixed-integer quadratic solver

Solving for $\Delta \bar{U}_{zk}{}^*$ under the constraints in equation (9.9) does not always provide a final solution for a given control time step. Specifically, the circuit breaker constraint $0 \leq z_{ik} \leq 1$ often does not result to exactly 0 or 1. Thus, a branch-and-bound procedure if followed: First, the original problem is solved, and the discrete variables are allowed to attain continuous values. This is called bounding, and provides an optimistic estimate for the mixed-integer problem. If this relaxed solution is not feasible, the mixed-integer problem has no feasible solution.

If a feasible solution is found to exist with continuous values for the binary variables, the first binary variable is constrained to $1 \leq z_{1k} \leq 1 \leftrightarrow z_{1k} = 1$, and the optimisation of $\Delta \bar{U}_{zk}{}^*$ is repeated. Then, the constraint is changed to $z_{1k} = 0$, and the optimisation is again carried out. This is branching, where the problem is divided into multiple sub-problems.

If neither of the cases $z_{1k} = 1$ and $z_{1k} = 0$ provides integer results for the remaining binary variables, the branch-and-bound procedure is repeated for the next variable z_{2k}, first keeping $z_{1k} = 1$, and then $z_{1k} = 0$. This leads to a binary search tree (see figure 9.1) that grows with the number of binary variables.

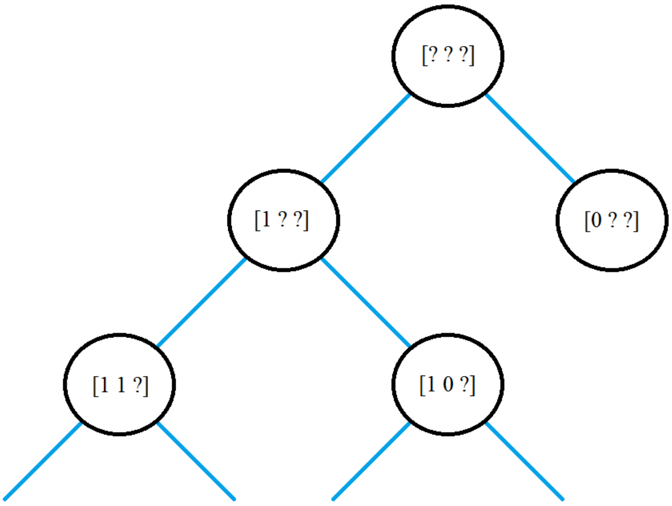


Figure 9.1: Discrete optimisation search tree. Untaken decisions are denoted by '?'.

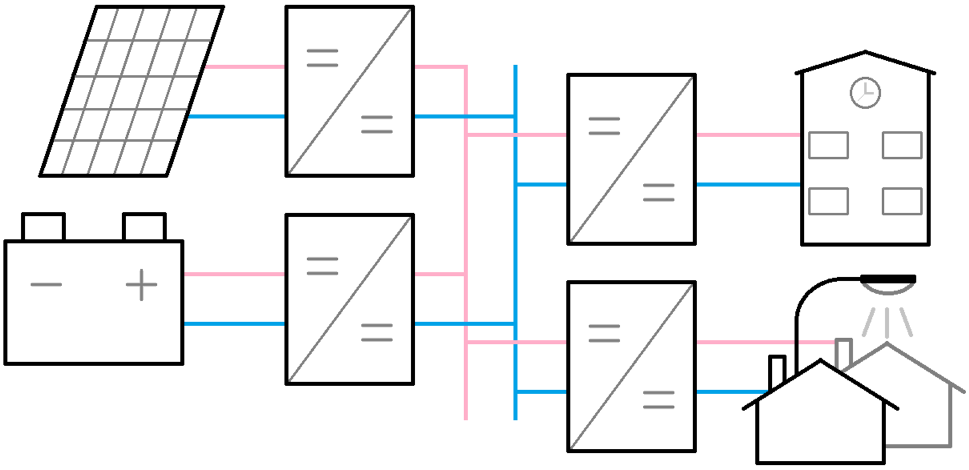


Figure 9.2: Schematic of the modelled microgrid.

The number of nodes in the binary search tree is $2^n + 1$ for n binary variables. To avoid searching the full tree for the optimal solution, a heuristic may be used to only search the most probable nodes. This implementation uses a depth-first heuristic that always examines the $z_{ik} = 1$ case before the $z_{ik} = 0$ case, as turning on the circuit breakers is desirable for the system. However, if one of the circuit breakers must be opened for time step k, then the algorithm will try to open it for time step $k + 1$ as well. This behaviour avoids excessive switching within the control horizon of a given time step.

9.2 Test scenario

For the testing of the MPC load management system, a realistic scenario of a renewable energy system was created. The system including weather conditions was modelled after Arunachal Pradesh, India, where one of the survey studies was carried out (see section 3.2.1). The system consists of a 1.3 kW PV installation, and an 800 Ah battery pack. Two types of loads are present, namely high-priority and low-priority loads. The high priority load is powered continuously, and the low-priority load receives electricity between 06:00 p.m. and 11:00 p.m. The former could be thought of as a public facility such as hospital or school, which would understandably need continuous power. The latter could comprise the households of a given village. As per the surveys presented in part I, most villagers are at work from early in the morning to approximately sundown, meaning that there is little demand during the day. As will be seen in part III of this thesis, these conditions are very similar to the actual implementation of the pilot sustainable energy system. Figure 9.2 provides a simple schematic of the simulated microgrid layout.

For the hardware-in-the-loop (HIL) simulation, realistic load measurements received from a small Indian microgrid were used to create the load profiles, and the maximum achievable PV power was calculated based on actual weather data from the region of Arunachal Pradesh, India[1]. The best-case and worst-case PV generation time series are shown in figure 9.3 Time

---

[1] The load measurements actually come from the pilot energy system installed in Arunachal Pradesh. The

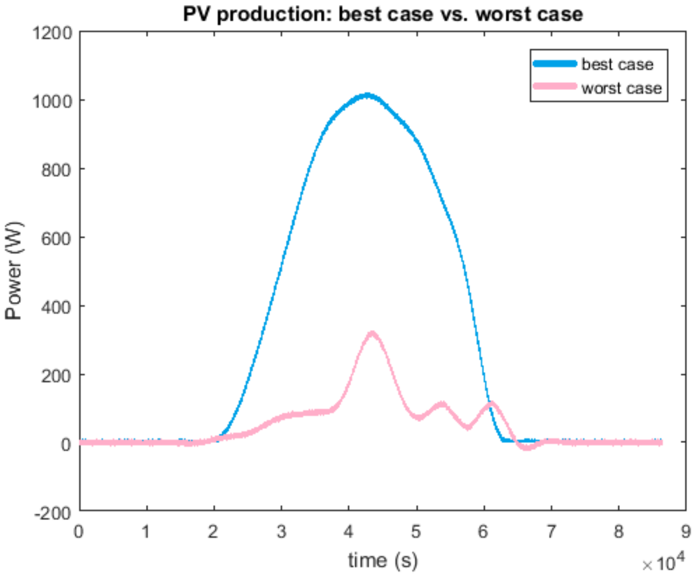


Figure 9.3: Comparison of sunny and cloudy conditions for the simulated microgrid.

on the x-axis is shown as seconds, and thus goes from $0s$ to $86400s$ in a 24-hour period.

The load profiles are presented in figure 9.4. The high-priority load is continuous throughout the day, and the evening sees a higher power consumption due to increased lighting needs. The low-priority load is zero until the evening when consumers are given power. Late in the night, the power is again switched off.

9.3 Implementation

To keep the cost of the hardware as low as possible, a cheap embedded system needed to be found. As before, a microcontroller of the Arduino/ATmega family was chosen, this time for the centralised system. More specifically, Arduino MEGA 2560 was used because of its increased computational capabilities compared to Arduino UNO. The MEGA currently costs around €35, making it very affordable even in low-cost energy systems.

The Arduino MEGA 2560 platform is based on the Atmel AVR 8-bit microcontroller ATmega2560 with 256 kB of in-system programmable flash and 8 kB SRAM. The MPC controller was implemented as a separate static library in C++, and included into the AVR firmware running on the ATmega2560.

The restricted SRAM limits the size of variables saved on the programme stack, and effectively prohibits the use of dynamic memory allocation. Consequently, the software design needs to make sure any auxiliary variables go out of scope as soon as they are not needed, and that the use of STL containers such as std::vector and std::map is avoided. Matrices and vectors are hence represented by fixed-size C-arrays. Additionally, any standard libraries were avoided, as well as the use of the Arduino.h header file.

---

design and installation of this system is extensively covered in part III of this thesis.

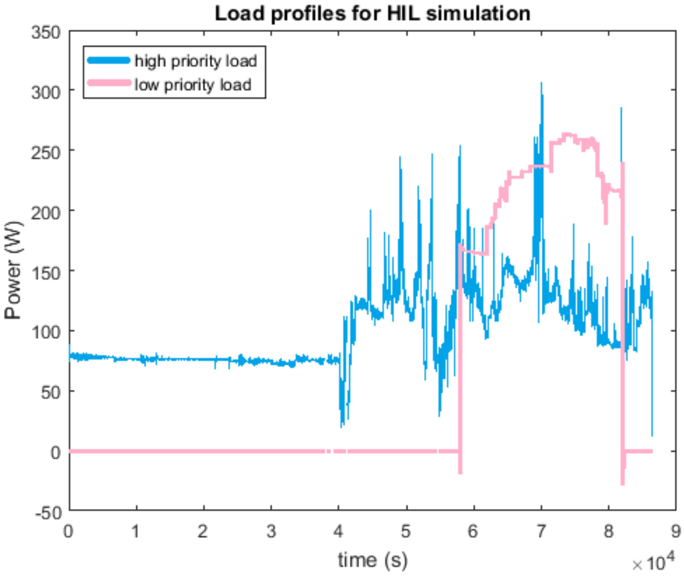


Figure 9.4: Load profiles for the simulated microgrid. The high-priority load is shown in blue, and the low-priority load in pink.

The control signals provided by the controller werew output through the Arduino MEGA digital pins, and measurements were received on the Arduino's analog input pins. The maximum pin voltage range of the Arduino is $0.0V - 5.0V$, which limited the accuracy of the measurements. The MPC controller was run at a time step of 10 seconds, and optimised for a horizon of three steps, i.e. 30 seconds. The prediction horizon was set equally to three. If the optimisation fails to find a feasible solution, the loads would be disconnected as a safety measure. Also, if the battery SOC sank under the allowed minimum of 0.4, or if overcharging occurred, the battery would be disconnected from the rest of the microgrid.

The microgrid model was created using MATLAB/Simulink and uploaded onto the OP5600 real-time simulator. The simulator executed the model at a fixed time step and ensured that it ran in real time. The digital control inputs to the microgrid model and the analog measurements from it went through a DB37 connection panel interfacing with the Arduino MEGA platform. All measurements were exchanged as voltage signals, and the Arduino and OP5600 were connected to a common ground. A schematic of the connections is given in figure 9.5.

The underlying microgrid comprised a PV generator, a battery system and two load lines of different priority. The battery was modelled as an ideal voltage source with constant voltage and a limited capacity. The PV installation was an ideal controllable current source, the maximum power output of which changes dynamically according to the time of day. It was assumed that the DC-DC converter of the PV line could be steered off the maximum power point if need be. This assumption justifies its controllability. The loads were modelled as constant power sources. All DC-DC converters in the grid were represented by simple delay blocks with no losses. Further, the switching devices modelled as part of the microgrid had an on-resistance of 0.01Ω. In total there were three circuit breakers in the grid: one on each load line and one emergency switch in case the battery SOC reached the limit of its operating range.

Two different scenarios were examined in the HIL simulation; the best-case and the worst-case

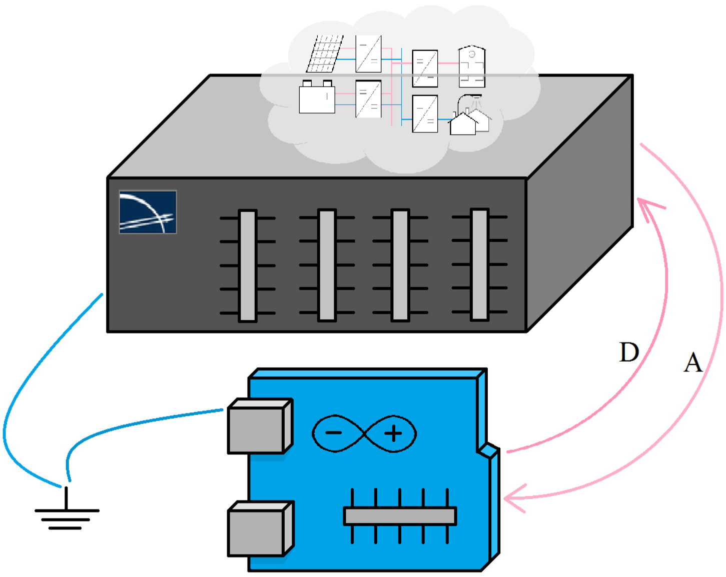


Figure 9.5: HIL setup with Arduino MEGA 2560 and OP5600. D stands for digital and A for analog signals.

Table 9.1: The specifications of the microgrid model.

Design specifications	battery	PV	load1	load2	SOC
	Microgrid component				
min. constr.	-960 W	0 W	0	0	0.4
max. constr.	960 W	1.3 kW	1	1	0.9
capacity	800 Ah	1.3 kW	-	-	-
bus voltage	24V				
time step	5e-5 s				

scenario. In the best-case scenario, the battery SOC was set high in its allowed operating range, and the sunniest day of the year was considered. In the worst-case scenario, the battery SOC was set very near its lower operating limit, and solar irradiation was weak. In either case, a full 24-hour period was simulated.

The details of the modelled microgrid have been gathered into table 9.1.

9.4 Results

Before doing a full hardware-in-the-loop simulation, it was necessary to test if the MPC algorithm works correctly. Hence, a software simulation was carried out before the HIL test. For this, the same specifications as detailed in section 9.3 were taken, apart from two adjustments: Firstly, the capacity of the battery is lowered to just 8 Ah. Thus the battery and the controller will react faster. Secondly, the load and PV time series are replaced with simplified signals. Figure 9.6 shows the power balance in the grid throughout the simulation.

The available PV power was kept constant at 1300 W, but the MPC algorithm correctly restricted its control input when the loads decreased and the battery reached its maximum charging rate at $60s$. At around $100s$, the battery SOC reached its maximum limit, and the PV power reference was further curtailed to avoid overcharging the battery. At $240s$, the high-priority load increased to $2000W$, which forced the MPC algorithm to disconnect the low-priority load in order to maintain a power balance within the grid. The battery SOC estimated by the Kalman filter, along with the cost function, are also plotted in figure 9.6.

Finally, in figure 9.7, the state of the load circuit breakers is plotted. As expected, the high-priority load stays connected for the duration of the simulation, whereas the low-priority load is disconnected at $240s$. Additionally, the relative effort of the MPC algorithm is shown. Clearly, nearing a constraint forces the algorithm to go through more iterations to find an optimal control input.

Next, the actual HIL simulation was carried out. The best-case scenario was tested first, followed by the worst-case scenario. Each simulation ran for 24 hours.
In the best-case scenario, the initial battery SOC is 0.8, and solar radiation is optimal throughout the day. This is an easy case to solve for the MPC algorithm, and a solution was found within 0.61 seconds even on the ATmega2560. The current flowing to and from each component in the microgrid is plotted in figure9.8, along with the bus voltage. In the early morning, the battery supplied the high-priority load in the absence of solar power. Later in the day, the PMS was able to utilise the maximum available PV power and satisfy the power demand. Any excess power was sent to the battery to further charge it. In the evening, when the high-priority load increased and load was added on the low-priority line, the battery switched from being charged to discharging power to satisfy the current need. The slight alteration in the bus voltage was due to the non-ideal switching devices.

Figure 9.9 shows the state of the load switches throughout the day. Clearly, both lines were successfully maintained irrespective of the amount of available solar irradiation. Note that the low-priority load was zero until $6:00p.m.$, and hence the MPC algorithm chose to keep it connected. An additional time switch in the microgrid automatically turned on in the evening and off in the morning to regulate the low-priority loads' supply electricity supply.

In the worst-case scenario, the available PV power was far lower than in the previous case (see figure 9.3), and the battery SOC started at 0.45, very near its lower operating limit. Figure 9.10 shows the grid voltage and the current measured at each component.
Again, the MPC algorithm was successful in optimally sharing the available power between the two load lines, and the battery was briefly charged during the peak sun hours. It is evident, however, that the battery was under more load than in the previous scenario, and that it could not maintain the same SOC as at the start of the day. Multiple consecutive days of low solar irradiation would lead the microgrid to a state where loads would have to be shed to maintain power balance. Finally, figure 9.11 shows that both loads were maintained without interruption.
The results presented above make clear that the MPC algorithm works and can successfully balance produced and consumed power within a microgrid. Nevertheless, the centralised control scheme has some obvious shortcomings and substantial room for improvement.
Firstly, the centralised MPC scheme puts a high computational load on the ATmega2560 chip, which is very limited in SRAM and flash memory (see section 9.3). This greatly limits

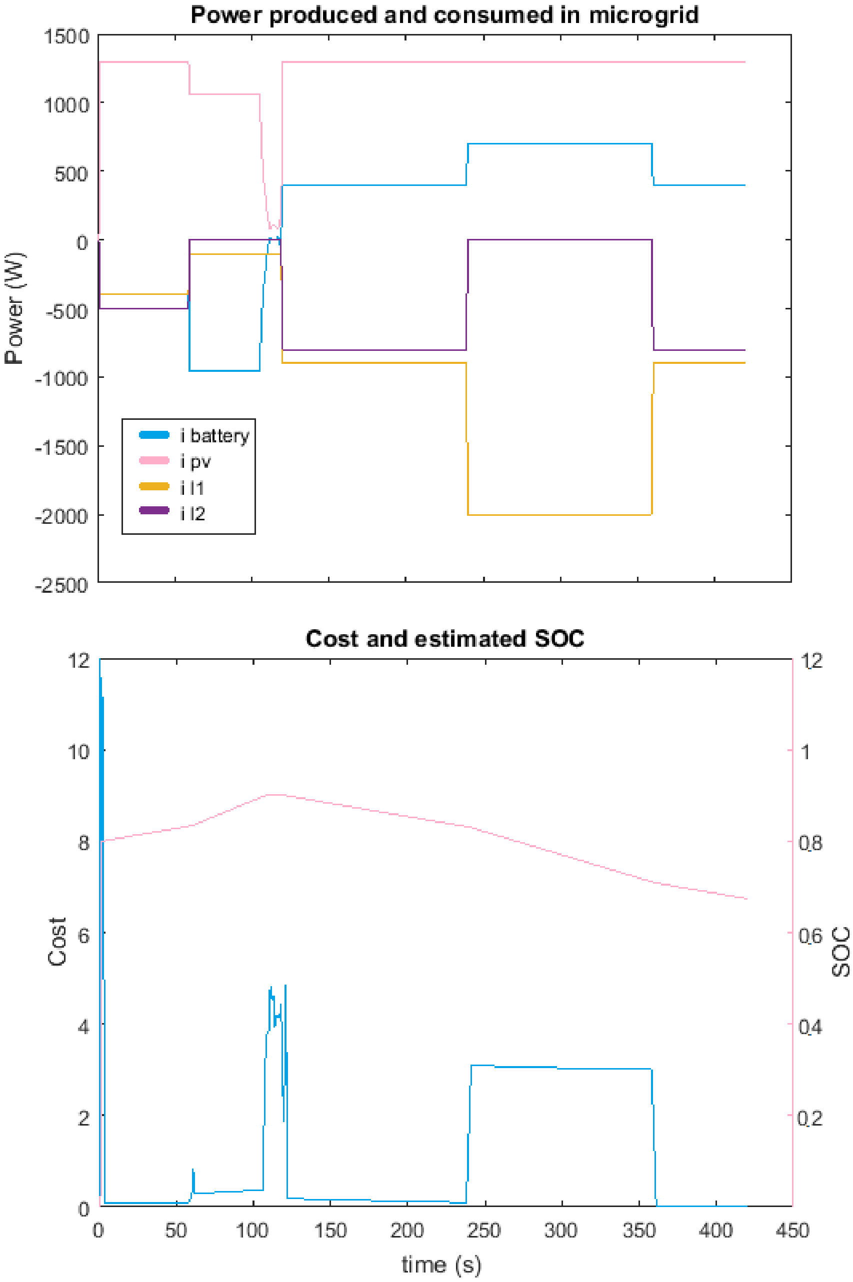


Figure 9.6: Above: bus voltage and current of the microgrid components in the best-case scenario. Current is negative when being consumed. l1 stands for high-priority load, and l2 for low-priority load. Below: the cost and the estimated SOC of the MPC algorithm.

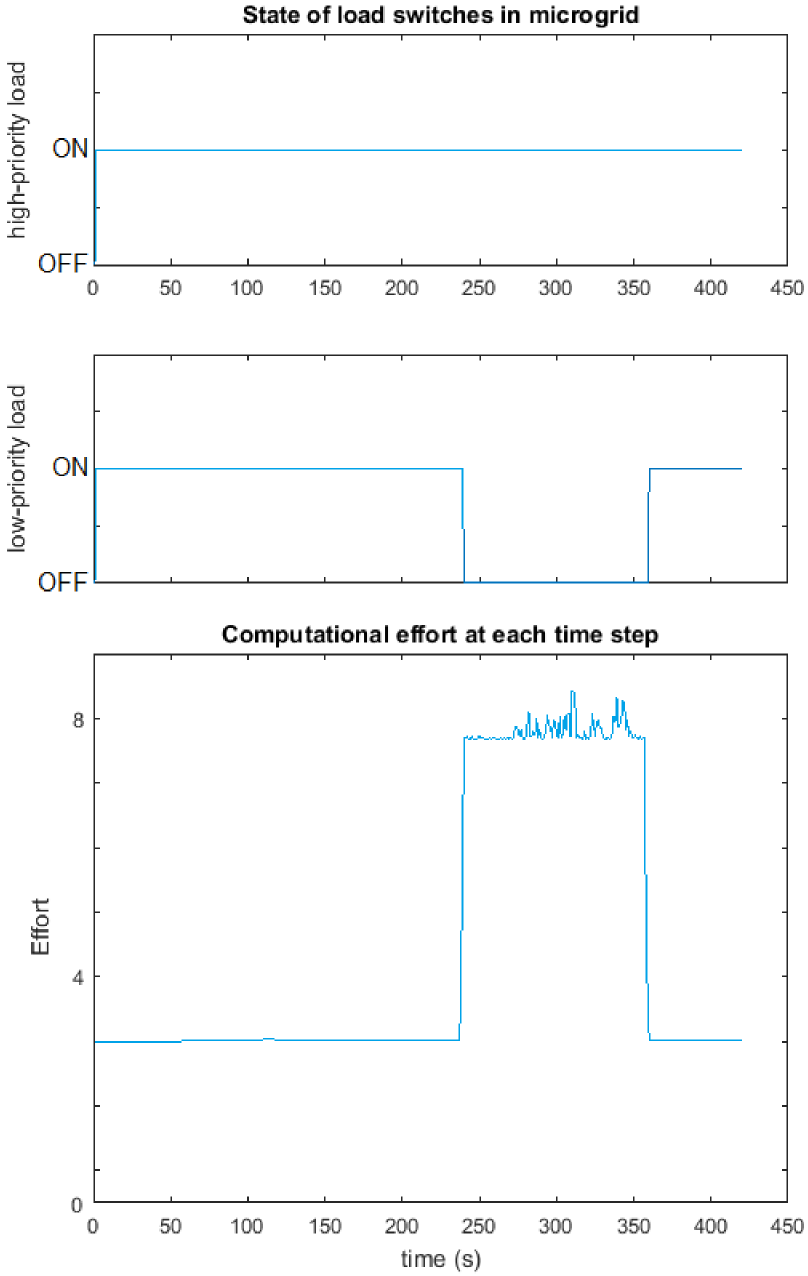


Figure 9.7: Above and centre: state of the load switches in the microgrid. Below: relative computational effort of the MPC algorithm during the simulation.

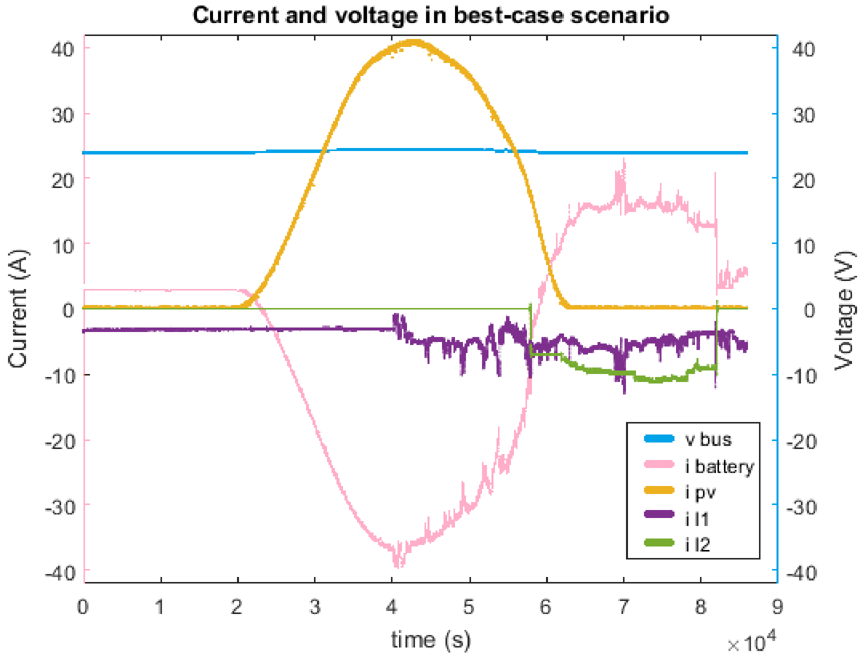


Figure 9.8: Bus voltage and current of the microgrid components in the best-case scenario.

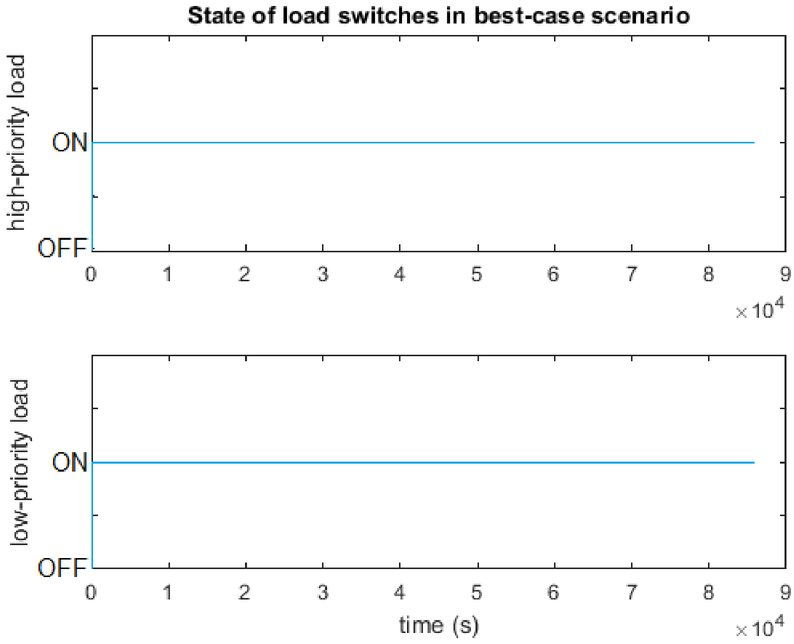


Figure 9.9: The circuit breakers controlling the load lines of the microgrid in the best-case scenario.

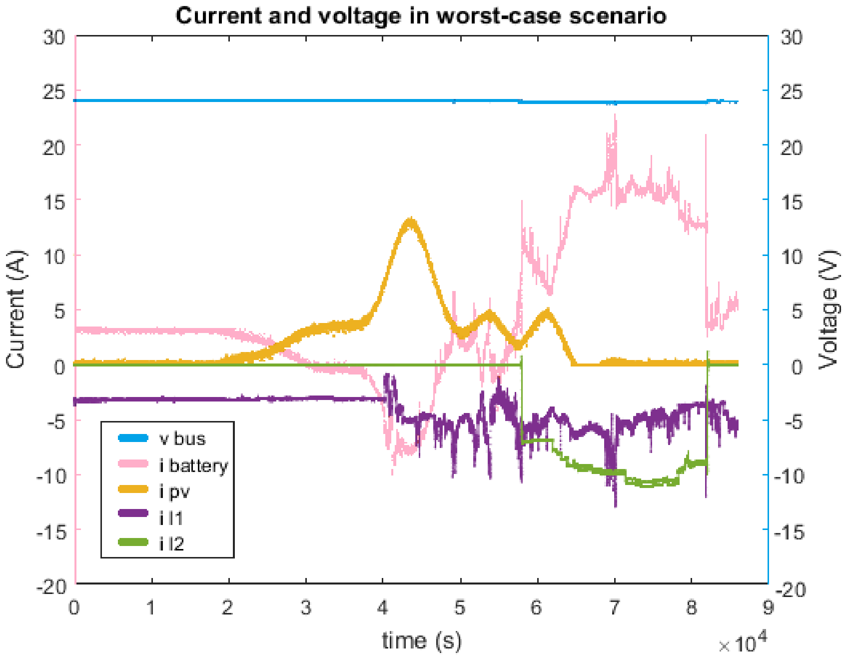


Figure 9.10: Bus voltage and current of the microgrid components in the worst-case scenario.

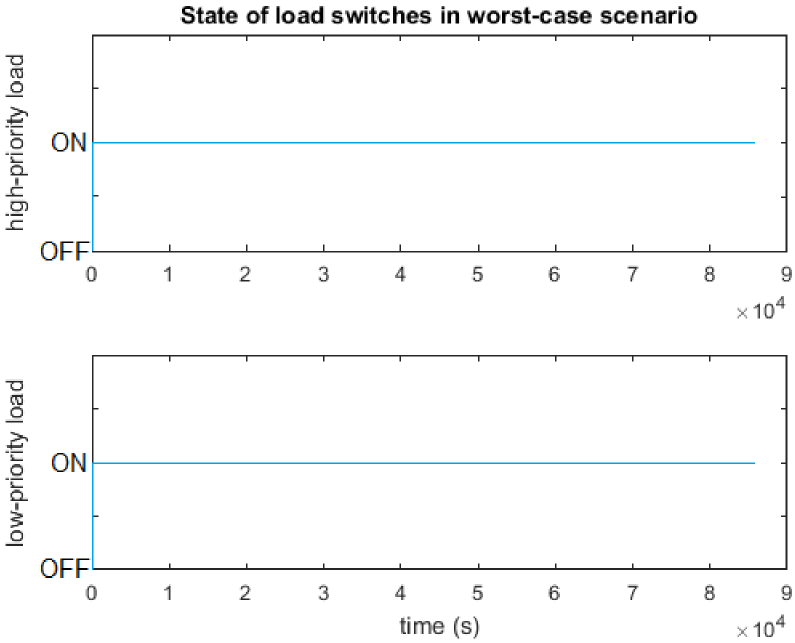


Figure 9.11: The circuit breakers controlling the load lines of the microgrid in the best-case scenario.

the functionality of the control algorithm, as increasing the optimisation horizon or number of microgrid components is very complicated without exceeding the strict memory constraints. To further improve the algorithm, moving to a more capable platform within the same price range would be essential, even though this obviously brings up the hardware costs. Secondly, a centralised algorithm is always vulnerable to a single-point of failure, and to avoid this, the MPC problem should be decomposed and decentralised. Splitting the code would potentially also mitigate the memory usage issues mentioned above, but simultaneously put a burden on any communication between controllers.

Moreover, the algorithm itself could be further improved. At present, the time step of the control is 10 seconds, but if Hildreth's programming procedure has not converged by that time, suboptimal results are produced. Solving the convex quadratic problem is the most time-intensive step of the algorithm. At every time step, the quadratic optimisation problem (and thus Hildreth's procedure) may have to be solved multiple times. Clearly, finding more efficient heuristics to prune the search tree is paramount to improve the controller performance overall.

Chapter 10

Discussion

This chapter compares the results of the case studies introduced in the last two chapters and takes a decision on which of the tested load management systems should be used for a pilot installation. For the comparison, the requirements set on hardware and software in sections 7.2.1 and 7.2.2 respectively, are utilised.

The rule-based system is distributed, with a main controller and three auxiliary controllers working together to ensure stable power supply. Each of the 12 households lines are measured for current, and voltage is measured once on the combined household distribution line. Additionally, two high-priority lines are sensed for current and voltage. The load management is thus very flexible and control each household separately. The control algorithm is simple and reacts instantly to changes in the microgrid, but lacks the capability of optimising power flow.

The load management system based on model-predictive control is centralised with a single central controller. Only two lines are defined, each with different priority. Current measurements are needed at each component to know how much they are consuming from or supplying to the microgrid. A predictive model with Kalman filter is utilised to optimise the future trajectory of each component, and thus providing stable power with optimal utilisation. However, households are treated as one aggregated load, and there is no possibility to control the behaviour of single households.

Comparing hardware for each case study is trivial as the same hardware family was used. Arduino is a very cheap platform and accessible worldwide which makes it an ideal choice for a load management system. The retail price of Arduino UNO is €19.00, whereas Arduino Leonardo costs between €14.00 - €18.00. Finally, the Arduino MEGA used in the MPC case study costs around €35.00. And for lower budgets, cheap copies of the Arduino microcontroller family may be found for as little as €a piece, even though they come without any warranty.

The hardware cost of both of the tested load management systems is similar, and well below €100.00 for the controllers alone. The overall price of the rule-based system is slightly higher due to the higher number of controllers and the fact that more measurements are made within the microgrid. This is because the rule-based system monitors each household separately, whereas in the MPC implementation current and voltage sensing devices are needed only for the aggregated load, and the components supplying power.

In terms of effectiveness, the hardware choice was fitting for the rule-based system, as each of the controllers has a simple task that may be executed without delay. The MPC system is also able to reach its real-time requirements, but its performance deteriorates when the microgrid deviates from favourable operating conditions. The more averse the circumstances under which the controller needs to operate, the less effective it becomes. The optimisation takes more and more time and it becomes essential to break off the iterative calculation (Hildreth's programming procedure, see section 9.1), which leads to suboptimal outcomes.

The robustness of the load management systems is also not equal even though similar hardware is used. Both systems suffer from the risk of single-point of failure because the main controller of the rule-based system decides whether or not to power up the auxiliary controller. In the case of the MPC impelemtation, it is obvious that if the central controller is damaged, no further operation of the load management system is possible. However, the flexibility and modulatiry of the rule-based system allows for at least partial operation with relatively few changes is problems occur. And if one of the auxiliary controllers fails, the rest of the microgrid can still operate. Hence it is clear that a distributed control system adds robustness to the microgrid.

Ease of maintenance is very difficult to achieve with control systems, especially when introduced to communities with no prior experience of electricity. However, Arduino microcontrollers are available worldwide and are hence easy to replace. The platform is also very user friendly, and easy to understand. Further, both load management systems were designed for little or no consumer intervention, which simplifies use and maintenance. The community will only need to ensure that the controllers are powered up in order for them to work as intended. The power need of the Arduino platform is very low, and both suggested load management systems receive their power straight from the microgrid that they are controlling.

The difference of rule-based and MPC load management becomes more evident when comparing them against the software requirements defined previously. In terms of computational needs, the MPC implementation surpasses the rule-based system in complexity and computation time. The rule-based system reacts quickly to alterations in the microgrid whereas the MPC system loses time going through its optimisation algorithm. In case of highly adverse operating conditions, the optimisation procedure takes several seconds and may fail to react quickly enough to harmful deviations in voltage or current. It is clear that the MPC system will potentially have difficulty in reaching its real-time goals, resulting to suboptimal control actions. Further, the algorithm may grow unstable in the most unfavourable scenarios. None of these issues affect the rule-based algorithm which trades optimality of results for added robustness and guaranteed real-time performance.

The MPC implementation has an added disadvantage in that its scalability is very bad. The current implementation is already pushing the limits of the Arduino MEGA platform, so in case more components are added to the system, a different platform altogether would have to be chosen. Due to its centralised approach, simply adding another controller is out of the question. Conversely, the rule-based system is very flexible and easy to expand. Adding an auxiliary controller needs no alterations to be made at any of the existing hardware or software, which adds to the systems user-friendliness as well.

After this comparison the decision is clear. Event though model-predictive control is an effective and promising method for load management in general, the strict hardware requirements of rural electrification make implementing such advanced methods difficult at best. At worst, they reduce the robustness and efficiency of the microgrid. Hence, the simple rule-based shall be implemented as part of the pilot renewable energy system. A summary of the comparison of

Table 10.1: Comparison of hot the rule-based and MPC load management systems address hardware and software requirements.

Requirement	rule-based	MPC
Hardware cheapness	low	low
Hardware effective	high	medium
Hardware robustness	high	medium
Hardware ease of maintenance	medium	medium
Hardware user-friendliness	high	high
Hardware power needs	low	low
Software computational needs	low	high
Software real-time capability	high	medium
Software robustness	high	low
Software user-friendliness	high	low
Software scalability	high	low

the two load management systems is given in table 10.1, and the details of the implementation of the sustainable microgrid are presented in part III of this thesis.

Part III

Sustainable design and implementation of a renewable energy system in Arunachal Pradesh, India

Chapter 11

Intro

Parts I and II of this thesis have thoroughly discussed the issues faced by small renewable energy projects in rural regions of the world. First, energy demand was determined based on surveys on households level and among community stakeholders. The suitability of the surveyed locations was studied based on availability of resources, the locals' willingness and ability to pay, the presence of productive use cases, and the wider cultural context.

Second, reasons for the lacking adoption of renewable technologies were investigated based on the factors affecting such projects. Based on these results, a barrier-based framework was created for the assessment of renewable energy projects. This framework lends itself for both the pre-assessment to see whether a given project could be successful, or to post-assessment of already existing projects to analyse why they succeeded or failed.

Part II concentrated on finding a low-cost load management solution to improve power quality within small off-grid power systems. Power quality was previously identified as the most significant technical barrier to rural electrification, and hence deemed worthy of mode in-depth analysis.

Part III introduces a pilot project for a sustainable off-grid power system installed in the village of Jamupani in Arunachal Pradesh, India. The project's goal was to show that by taking into account the findings of parts I and II, a safe and robust energy system could be designed with guaranteed improvements to the quality of life of its users. The system would meet the needs and wants of its end-users, and at the same time be easy to operate and maintain. To reach these goals, an extensive energy needs survey was conducted, and the barrier-based framework of section 4.2.2 was applied to the chosen location to understand the lack of energy in a wider context. The results obtained in part II were directly applied to the pilot energy system in the form of a distributed rule-based load management system.

11.1 Jamupani

Jamupani is one of the villages visited as part of the India energy needs survey detailed in section 3.2.1. It is situated in the mountains of the pre-Himalayas in the state of Arunachal Pradesh, and home to 12 households and approximately 50 inhabitants. Additionally, Jamupani has a government residential school with 55 pupils from around the Lower Dibang Valley

Figure 11.1: Aerial photograph of the village of Jamupani. the building complex at the top is the Jamupani government school[92].

district, and a staff of 10 people. The pupils and the staff live at the school premises for nine months a year.

Jamupani is very remote with no road access and no reliable mobile nor internet connectivity. The only way to reach the village is by hiking for 1.5 hours from the nearest seasonal road, which is plagues by frequent land slides in the rainy season. Figure 11.1 shows an aerial photograph of the village.

The main reasons for choosing Jamupani as the implementation site for the sustainable energy system pilot project was the clear productive use case provided by the school. Electricity was considered to positively impact the learning results of the pupils, and thus improve their prospectives in life in the long run. Additionally, supplying the school with electricity would serve other communities as well because many of the pupils come from surrounding villages. Another reason to install a power system in Jamupani was the possibility of harnessing the non-seasonal stream flowing through the village. This assures that power could be provided even in the rainy season when solar irradiation is at its lowest.

According to the government, Jamupani already had the satus of being electrified due to a failed attempt at electrification in the early 90's. The village had received electricity for a day or two, after which the government-built system had fallen into disrepair. However, Jamupani still officially had access to electricity, potentially discouraging the local government from providing grid electrification. Additionally, their electrification status bars the community from receiving subsidies for solar products.

11.2 Factors affecting renewable energy systems in Jamupani

Based on the initial energy demand survey of Jamupani, the village had a lot of potential to successfully adopt a renewable energy system. The necessary productive use case was present, the community was in favour and willing to pay a monthly service fee, and resources were plentiful for power generation. However, the village had experienced great neglect by the local government following a failed attempt to electrify it in the early 1990's, and are not eligible for subsidies for renewable energy based on their status as electrified. This factor was identified as the major obstacle to Jamupani receiving power without foreign intervention. Further, due to its remote location, it had not evoked the awareness of large non-governmental organisations.

The findings of the energy demand survey were mirrored by the framework of barriers introduced in section 4.2.2. The results of applying the framework are presented in table 11.1, and clearly show that the government's absence and the lack of support has been hindering the adoption of renewable energy in the village.

Table 11.1: The framework of barriers used to assess the village of Jamupani in Arunachal Pradesh.

Barrier	Impact	Comments
`Government absence and lack of proper institutionality`	medium	The local government has neglected to electrify Jamupani after a failed attempt in the early 1990's. However, the government showed interest in taking over the new system if the installation was successful, even promising to take responsibility for its maintenance and financial support.

Lack of proper legistaltion & regulation	medium	Jamupani officially has the status of being electrified, and hence is not eligible for subsidies for solar power, nor will it be considered for another electrification attempt by the government. Still, a privately-built energy system would be taken over by the local government.
Lack of qualified human capital & environmental awareness	low	The Further & Beyond Foundation partnering with this project has a clear sustainable goal of electrifying villages with renewable energy. They also operate in the waste sector trying to minimise electronic waste. They are active in training and educating local communities on sustainability. Further, most rural communities in Arunachal Pradesh are familiar with solar power and use a number of small-scale solar products already.
High investment costs	low	The goal of the Jamupani microgrid was to maintain a low budget, and many of the components were obtained as donations from interested companies working in renewable energy. This way, the Jamupani microgrid could be installed with very low capital cost, and with no initial cost for the end-users.
Misconception of the role of community	low	After a through survey of the village of Jamupani and the most important stakeholders, their needs and wishes were taken into account throughout the design process of the microgrid. The community was asked what appliances they wished to use and the design was adapted to realise those wishes.
Subsidised LPG generation	low	Even though LPG is subsidised in Arunachal Pradesh, the lacking infrastructure makes obtaining it near impossible. Hence, the local interest for completely autonomous means of power production is high.
Lack of partnerships for development	low	Small NGOs are active in the area, introducing solar lanterns and small PV panels to local communities. The Further & Beyond Foundation was willing to support this project from the first field visits to the final implementation. Further, many Indian companies would actively support small-scale electrification projects with material donations.

`Informality`	low	The project was discussed in depth with local community leaders and public stakeholders such as the Jamupani governmental school headmaster. Official permits to implement were obtained from the local government, and a handover of the successful installation was agreed upon.
`Poverty`	medium	Even though most villagers could not afford the capital investment of installing a renewable microgrid, most are relatively wealthy due to cultivating cash crops such as cardamom and yam. Thus, they are willing and capable of paying for electricity services on a monthly basis.
`Problems of social order`	low	There is some opium production in the mountains of Arunachal Pradesh but the cultivators are not financially dependent on competing forms of energy and thus pose no threat to renewable energy systems.
`Corruption`	low	Levels of corruption in the local governments is relatively low, and they have no financial interest in hindering the advancement of renewable energy projects.

Based on the initial energy demand survey of Jamupani and the framework of barriers, a sustainability strategy for the Jamupani microgrid could be created. This strategy is simply a list of measures that would need to be taken to ensure the long-livedness of a renewable energy system in the village.

11.3 Objective

The objective of this part of the thesis was to implement a sustainable pilot project for a remote renewable energy system. Based on the research discussed in part I, many social, economic and political issues create obstacles that hinder the advancement of renewable energy in the rural context. The main objective of pat III was then to show that by identifying these issues early on, and by addressing them throughout the design and implementation of an off-grid system, that system could be made to last.

Additionally, one particular technical barrier to renewable energy was identified; power quality. Bad power quality was shown throughout the studies conducted in India and Nepal to dissuade users from adopting electrical connections, and to refuse for paying for the service in already-connected areas. Part II of this thesis went into detail on how load management systems can be beneficial in mitigating power quality issues, and such a system was also implemented into the pilot project presented in the following chapters.

More practically, the objective was to implement a reliable and safe power supply system for the government residential school and the inhabitants of the village of Jamupani. Based on the energy needs survey discussed in section 3.2.1, and the application of the framework of barriers, the following objectives for the sustainable pilot projects were set:

- Design and implementation of robust and safe microgrid that uses locally available renewable energy
- Continuous AC power provided to Jamupani government residential school
- AC power supplied to 12 households daily between 18:00 and 23:00, and to outside lighting between 17:00 and 23:00
- Training of locals to operate and maintain the microgrid

11.4 Sustainability considerations

As shown by the findings in part I of this thesis, a myriad of social, economic, cultural and technical factors create obstacles to the advancement of renewable energy systems in the rural regions of the world. The underlying hypothesis of this thesis was that by identifying these barriers early on in the process of developing a sustainable microgrid, they could be effectively mitigated, leading to a successful, robust and log-lived energy system with a positive impact on the local community.

The barrier framework showed that government absence and lack for proper legislation were issues preventing Jamupani from receiving power. However, after the TUM expressed interest in building a microgrid in Jamupani, the government had no objections, and even agreed to take over the system once successfully installed. Thanks to the active help of our NGO partner and of a very engaged local leader Anjite Menjo, the lack of direct government support was not problematic to the project. Through the local expertise of our partners, the design and installation of the system could be fully co-ordinated without government officials actively stepping in. The step of finding a trustworthy local partner cannot be underestimated, as they have essential insight into the culture and customs of the target community, and they help immensely in gaining the trust and appreciation of the villagers.

Based on the findings of the initial survey and the factor assessments detailed in part I, the following requirements were set and fulfilled to promote the long-term community involvement, and thus the sustainability of the Jamupani system:

Appointment of a local system manager

Two members of the Jamupani village were chosen to be trained to maintain the system once installed. They were selected based on the suggestion of village elders and the school headmaster, and would be involved in the installation of the system as well as receive formal training once the installation was complete. They would be paid for their role from the monthly fees gathered from end-users of the microgrid. Further, an extensive maintenance plan with daily, weekly and monthly tasks would be provided to the local managers.

Solid payment plan

The end-users of the Jamupani microgrid would commit to paying ₹100 per month that would be used to pay the wages of the two system managers. Further, the school agreed to pay ₹500 per month for using the system. After the takeover by the local government, public funds would be used to financially support the maintenance of the microgrid.

Long-term sustainability plan

The system was intentionally oversized to accommodate for increasing energy need in the future. It was projected that most households would increase the time used watching TV, and that the school would obtain one to fulfill their curricular requirements. Further, the school was to be provided with a secondary power line in order to use laptops as part of education.

Training

The selected system managers were to be trained extensively on the system, but all the end-users would also receive individual instructions on how to use the system safely. This would include teaching them what appliances could be used with AC power as well as what to do in case of emergencies or malfunction.

Ensuring stable power quality

A carefully designed modular load management system would be installed as part of the microgrid to ensure stable power supply to all end-users. As discussed in part II, a distributed rule-based strategy implemented on the Arduino platform would be implemented.

Installation of technical safety features

To minimise the risk of possible malfunction of the microgrid, various technical safety features were to be implemented. These range from lighting arrestors to safe cabling and integrated MCBs. Emphasis was given to user safety even in case of system failure.

Communication and community involvement

From the first site inspection, utmost care was taken to involve the community of Jamupani in all decision making. Villagers were consulted to design the system according to their needs, and their suggestions were taken into consideration when installing the system components and distribution system.

All the above measures were carefully planned during the design phase of the system, and successfully realised during installation. The following chapters will provide further details of the fulfillment of each of the above requirements.

Chapter 12

Design of Jamupani microgrid

This section provides a comprehensive overview of of the design process that lead to the implementation of the Jamupani microgrid. Much of the design was based on the survey results detailed in section 3.2.2.

12.1 Electricity demand

One of the key pieces of information needed for a successful energy system design is the amount of electricity needed by the target community. The demand usually is not constant throughout the day, and is highly dependent on the number of potential consumers as well as the appliances and use cases that are either already present or desired by the community. In the case of Jamupani, the maximum consumption of the government residential school, and that of the households, needed to be estimated and aggregated to create a daily load curve. Here the maximum estimate was used to make sure that enough power would be available even during peak loads.

To estimate peak electricity demand, the survey data from Jamupani was utilised. During the survey, the existing appliances and their daily use patterns had been recorded, as well as the villagers' desire for new appliances. This data was aggregated and the resulting load curve is shown in figure 12.1. Based on this load curve, the maximum combined power demand of the village of Jamupani is $1.2kW$, and the peak occurs during evening hours when the villagers come back from work. As per the survey results, most inhabitants of Jamupani are subsistence farmers and work out on their fields from early dawn to sundown. This is clearly represented in the load curve. Outside of the peak hours the load was shown to be rather constant, never exceeding $500W$.

Using the survey results and the generated load curve to guide the planning of the Jamupani microgrid, the following initial design decisions were made:

- A hybrid renewable energy system would be installed, powered by PV panels and a micro-hydro turbine.
- The school would have highest priority, and would receive two separate power lines. One line would provide continuous power to the school and cover its basic electricity need, including light, mobile-phone charging and a TV set for educational purposes. The other

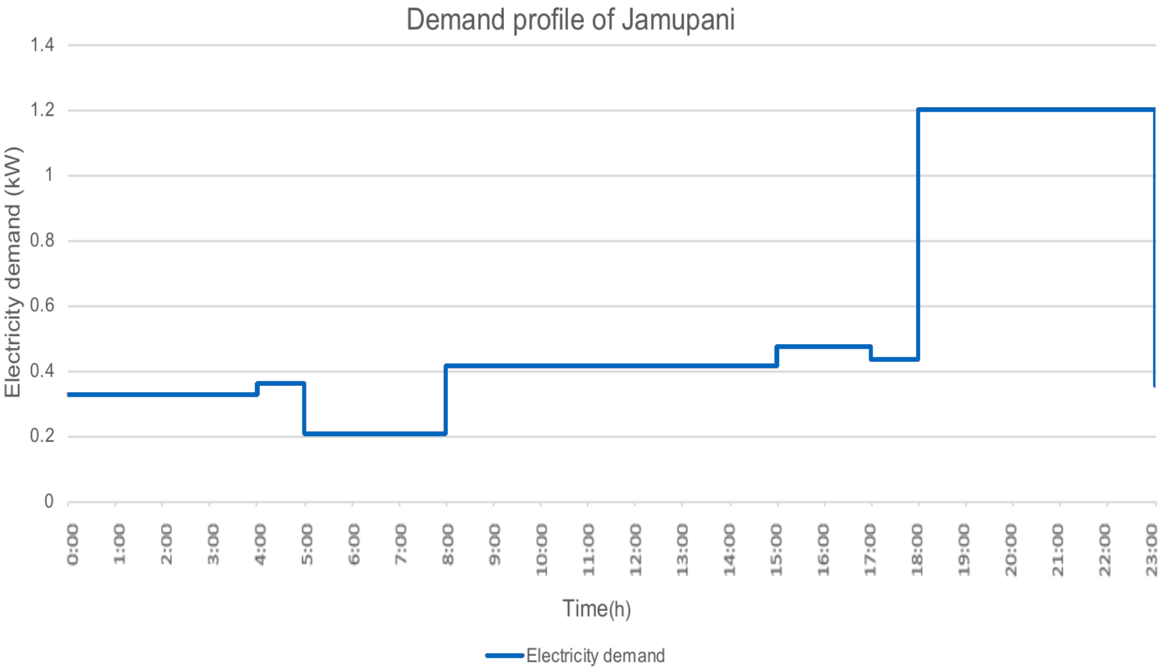


Figure 12.1: Jamupani demand curve[93].

line would power laptops if needed. At the moment, the school does not own computers. Both lines would be sized for an average load of $300W$.

- A load management system would regulate how much power is drawn by each of the two lines, cutting the supply off in case the maximum of $345W$ was exceeded.
- Each of the households would receive $60W$ of power each. This is sufficient to power a few LEB bulbs, a mobile charger and a TV set including a set-top box and a satellite receiver. These were appliances that the villagers were the most keen on using.
- A load management system would cut off any household's power supply for a specified amount of time if its consumption surpassed the allowed $6oW$.
- $25W$-rated streetlights would be used to light the public areas of Jamupani after sundown. A total of seven streetlights would be utilised.

During the installation, some of these design decisions had to be changed. More details on this will be provided in chapter 13.

12.2 Power generation

The power need within the Jamupani microgrid was to be covered by a combination of PV panels and a micro-hydro turbine. The PV installation would produce a peak of $1.3kW$, and $1kW$ would come from hydro power. The system would thus have a peak production of $2.3kW$, and the peak power requirement would hence easily be covered. The reasoning behind having two power sources was to generate the continuous power needed by the school with the micro-hydro turbine, and to have the PV system generate the power needed by the villagers. It was estimated that the nominal power production would be the required $1.2kW$, with about

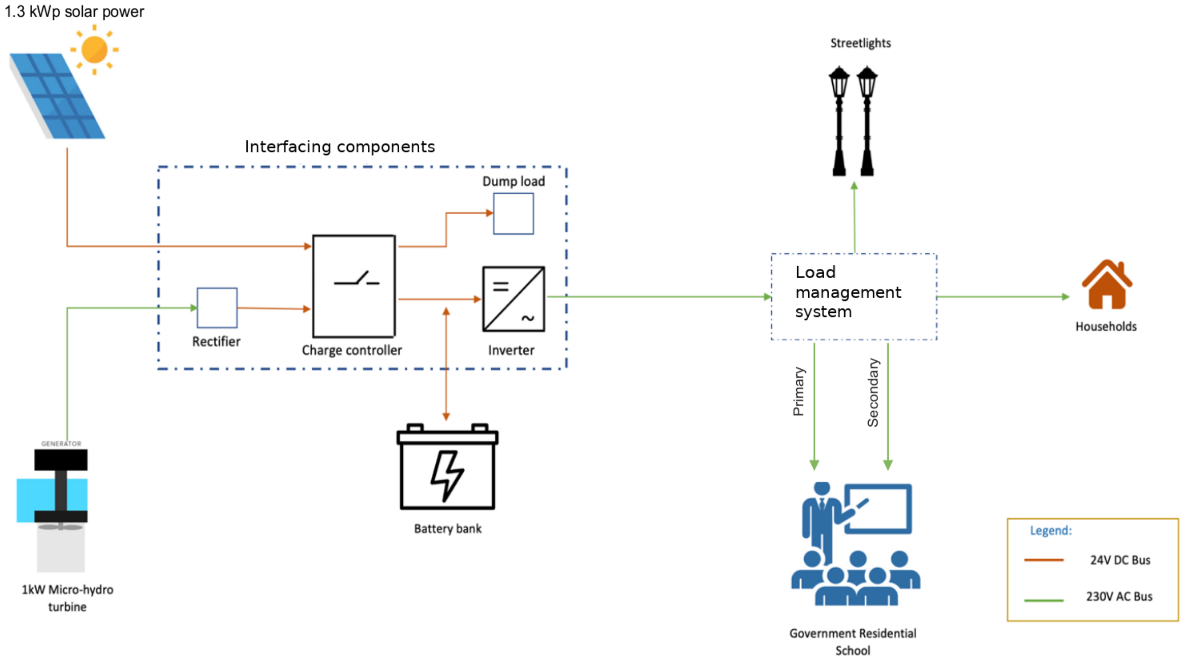


Figure 12.2: Layout of the hybrid PV and micro-hydro energy system for Jamupani[93].

$600W$ produced by both power sources.

Because the PV system reaches its peak power generation during midday, a battery-based storage system was added to the design to shift the generated power to the evening when the peak load would occur. The battery system would consist of four $200Ah$ batteries. This would keep the depth-of-discharge (DOD) at less than 50 per cent even in times of low solar irradiance, and thus increase the lifetime of the battery bank.

The energy system design was clearly oversized compared to the actual demand. This was a concious decision to take into account possible losses in the hydro-power system, bad weather conditions and lack of water in the dry season. Even though the stream flowing through Jamupani is non-seasonal, its flowrate significantly decreases outside of the Monsoon period. Further, oversizing the energy system makes it possible for villagers to increase their power consumption without altering the existing power system.

Based on the initial design decisions and the estimated power requirements, a layout of the Jamupani energy system was created. Figure 12.2 shows this layout.

PV system

The PV system consists of a set of solar panels totalling $1.3kW$. The panels were selected base don their availablility on the Indian market as well as their cost, size and whether or not they could easily be mounted on a rooftop. The panels would be installed on the south-facing rooftop of one of the buildings at the Jamupani school, mainly to increase the power output of the PV system but also to ensure that they are out of reach of the pupils of the school. Another consideration was to choose panels with a warranty.

Based on the above-mentioned criteria, Luminous $335W$,$24V$ poly-crystalline PV panels were

Table 12.1: Specifications of the selected PV panels.

Parameter	Luminous 335 W
`Cell type`	Poly-crystalline
`Rated power`	335 W
`Voltage (max. power point)`	38.92 V
`Voltage (open circuit)`	46.10 V
`Current (max. power point)`	8.06 A
`Current (short circuit)`	9.26 A
`Warranty`	25 years
`Number of panels`	4

selected[1]. Four such panels were needed to reach the required $1.3kW$, and a fitting PV combiner box was chosen to combine the power output of the panels. Table 12.1 lists the specifications of the PV system.

Micro-hydro turbine

Not all hydro power solutions are suitable for a given stream. Factors such as flow rate, available head, cost of the system, and its availability in remote areas need to be considered before selection. Additionally, the amount of civil work required to install the hydro system may be significant, and hence influences the decision as well.

The data collected from Jamupani during the energy need survey revealed that the local stream is non-seasonal but susceptible to overflowing during Monsoon season. The stream was additionally inspected during the survey visit, and satellite imagery of it was analysed. Based on this analysis, a turgo-type turbine was selected.

Turgo turbines need a relatively low discharge of water to generate electricity. This was an essential advantage over other small turbines as the stream loses much of its volume during the dry season. However, this type of turbines need a high head to generate power which could prove problematic. The terrain in Jamupani is fairly steep, and hence generating a high head for the turbine was not considered a obstacle.

The Vinci Aqua $1kW$ turgo turbine was selected because it has already been used in many similar projects across India. The manufacturer is Indian and spare parts for the turbine and piping are widely available. The Vinci Aqua turbine only needs a discharge of $12l/s$ and a head of $20m$. To generate this amount of head, a $120 - 150m$ penstock pipe would be required based on the satellite imagery. Figure 12.3 shows the elevation difference for a distance of $120m$ at the Jamupani stream. Additionally to the penstock pipe, an intake tank would be required to maintain a bubble-free input water flow to the turbine. The intake tank would also require an intake pipe from the stream to the tank, and a filter structure to make sure no leaves or pebbles get into the tank and the turbine. All of this requires a substantial amount of civil work. Adding to the amount of civil work is the fact that no road access to Jamupani exists. The Vinci Aqua turbine is fairly lightweight making it easy to transport manually.

Table 12.2 shows the specifications of the Vinci Aqua turgo turbine.

---

[1] Luminous is an Indian company that provides solar panels and battery systems across the country. They were kind enough to donate the PV panels and the battery system to Jamupani free of charge.

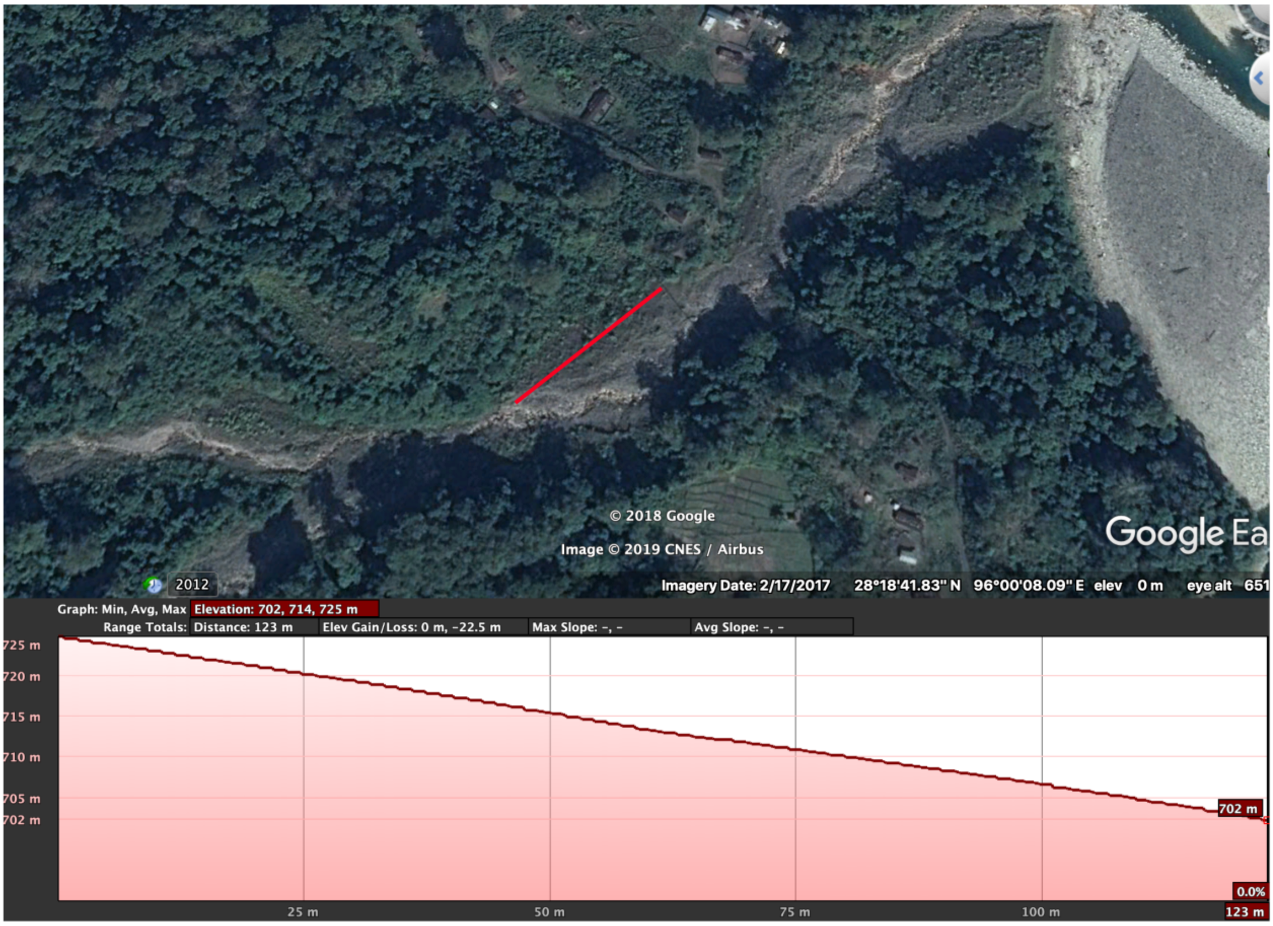


Figure 12.3: Satellite image and the elevation difference at Jamupani stream[93].

Table 12.2: Specifications of the selected microhydro turbine.

Parameter	Vinci Aqua 1KW turgo turbine
Rated power	1 kW
Power output type	Single-phase AC
Output voltage	230 V
Required head	20 m
Required discharge	$12 \frac{l}{s}$
Number of turbines	1

Table 12.3: Specifications of the selected battery system.

Parameter	Luminous LPTT 12200 L
`Capacity`	200 Ah
`Efficiency (Ah)`	90 %
`Efficiency (kW)`	80 %
`Filled weight`	65.5 kg
`Warranty`	3 years
`Number of batteries`	4

Battery bank

The battery system is needed to store the excess power during day-time, when supply surpasses the load, and to provide it back to the system during peak-load hours. The lifetime of a battery system is dependent on its depth of discharge (DOD) and the number of charge-discharge cycles it goes through. Hence it makes sense to oversize the battery system to limit the DOD to less than 50 per cent. Based on these considerations, a battery system minimum capacity of $7.5kWh$ was chosen.

Lead-acid batteries were chosen to create the battery bank, mainly due to their lower cost compared to lithium-ion and gel batteries, and due to their wide availability on the local market. Batteries are typically the priciest component of a off-grid energy system, and minimising their cost can make a significant difference.

Four $200Ah$, $12V$ lead-acid batteries were chosen for the Jamupani microgrid. The batteries would be combined in a series-parallel circuit to obtain a $24V$ battery bank and have a rated capacity of $9.6kWh$. The Luminous LPTT 12200 L batteries were selected because they are designed for solar systems and can handle many cycles. These batteries are guaranteed to last for at least 1500 cycles even at 80 per cent DOD. Further, the batteries have a low topping frequency of 8-10 months, making them user-friendly from the point of view of maintenance. Table 12.3 lists the main specifications of the battery system.

12.3 Interfacing components

The power generated by the PV system is low-voltage DC power, whereas the micro-hydro turbine produces $230V$ AC power. To combine the outputs of these generators safely, various interfacing components are necessary. Additionally, the battery bank would need to be connected to the microgrid, and its charging and discharging controlled based on available power.

The main component in the interfacing architecture is a hybrid charge controller that combines the PV and micro-hydro output and produces constant $24V$ DC power for the battery system as well as for an inverter. In order to combine the two power sources, the micro-hydro output is first rectified. For safety reasons, high-current diodes and emergency circuit breakers are also placed into the interfacing circuitry. Further, a dump load is directly connected to the charge controller, to serve as the last resort in case surplus power is present that cannot be absorbed by the battery.

The inverter takes the $24V$ DC output of the charge controller and inverts it to $230V$ AC before

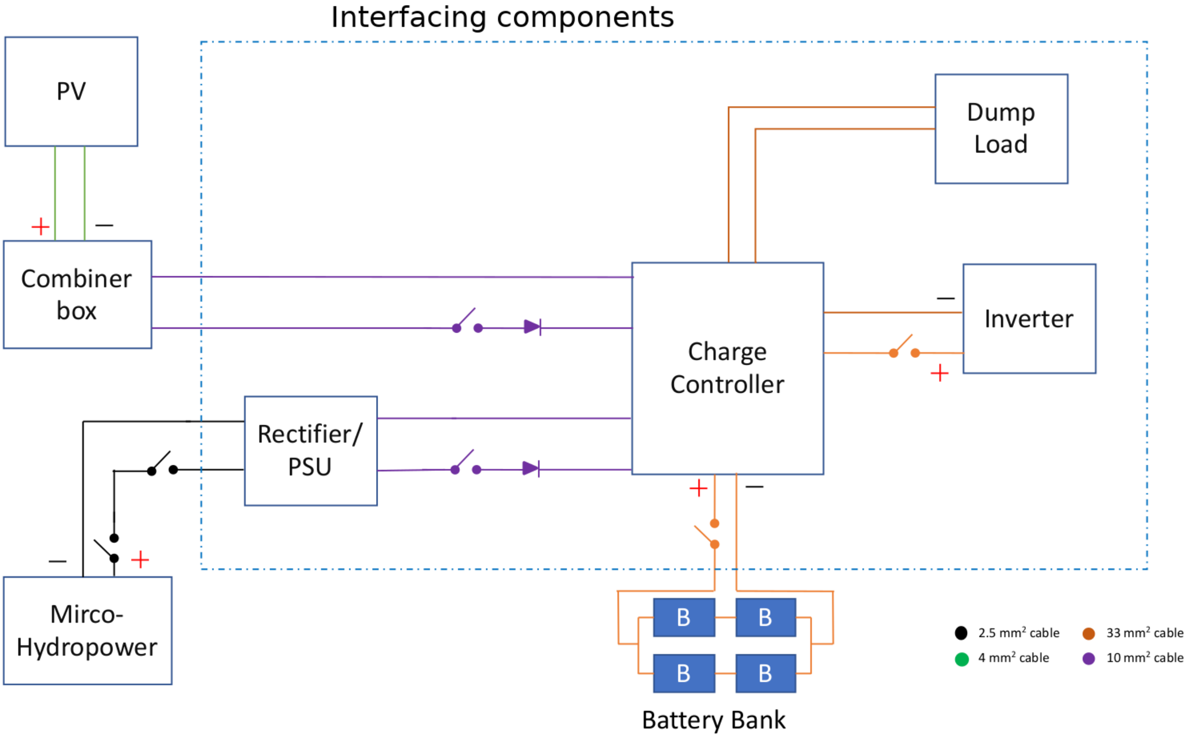


Figure 12.4: Layout of the interfacing components that combine power sources and storage[93].

serving it up for the connected loads. The $24V$-level was chosen for the DC side as the PV panels are rated for $24V$, and it is a standard rated voltage for many interfacing components. Additionally, if $12V$ had been selected, the peak current flowing through the DC side would have been close to $200A$, which is highly unsafe, and requires very thick and expensive wiring. Figure 12.4 shows the layout of the interfacing components that combine the power sources and the battery system to the load side of the Jamupani microgrid. A colour scheme has been used to show the different wire thickness within the system.

Rectifier

The rectifier placed between the output of the micro-hydro turbine and the charge controller turns the $230V$ AC power into DC. A $1kW$-rated component was needed for this purpose, and on that could handle a peak current of $41.6A$. The CUS 15000M-36 power-supply unit (PSU) by TDK Lambda was selected for the purpose. It is capable of handling high currents, and converts $230V$ AC to DC of $30.6V$ $43.2V$, which can safely be taken in by the charge controller. The chosen PSU has a rating of $1.5kW$ and a warranty of seven years.

Hybrid charge controller

The hybrid charge controller is the main interfacing component, and responsible for combining the two power sources with the battery bank and the rest of the microgrid. The main criteria for the controller were that it be capable of using two different power sources and to provide a DC output above $24V$. The component also needs to handle the combined power level of the power sources, and to route excess power to a dump load if needed. Due to the nature of the sustainable energy system project, safe operation, robustness and low cost were very desirable.

Based on the above criteria, a simple solenoid-based charge controller was selected over more sophisticated maximum-power-point tracking variants. The selected component is the C400-HVAD hybrid charge controller by Coleman Air. The component has three charge control modes: bulk charge mode, absorption charge mode, and float charge mode. The bulk mode sends all of the available current to the battery bank until the bank's voltage reaches a specified bulk set point, bringing the batteries to around 80 state of charge (SOC). Beyond this state, absorption charging takes over, maintaining the voltage level constant. This mode is active for a maximum of 120 minutes, bringing the battery bank to its full SOC. The float charge mode is then used to maintain the 100 per cent SOC by intermittently charging the battery bank.

Dump load

A dump load is typically simple resistive load with high power rating. The excess power is passed through the load to remove surplus power from the microgrid but in some cases it can be used to heat water or some other productive purpose. The L1000W24V dump load by Coleman Air was selected for the needs of Jamupani.

Inverter

The inverter converts the $24V$ DC power from the charge controller to the $230V$ AC used by most consumer appliances. For the needs of Jamupani, a pure sine-wave inverter was chosen as they are reliable and consume little power themselves. They are more expensive than simple square-wave inverters but also more robust. Further, the Luminous Cruze+ 2.5 KVA inverter was donated to the Jamupani grid without cost by Luminous. The inverter is rated for $2.1kW$ and thus matched the maximum rating of the designed energy system. This model is widely available in India, and hence replaceable in case of malfunction.

Dioides

As mentioned above, high-current diodes were used in the circuitry to block back flow of power, which could cause malfunction of some of the microgrid components. The selection of these diodes was based on the current rating. This side of the circuitry would need to withstand peak currents of around $50A$, and thus $85A$-rated Vishay VS-85HF diodes were chosen. These diodes generate a large amount of heat during operation and appropriate heat sinks were needed to dissipate it.

Circuit breakers

Circuit breakrs were needed in the microgrid to isolate different components from the charge controller in case of emergency. As with the diodes, the main selection criterion for the circuit breakers was the high current ratings, and thus $80A$-rated Truck Star circuit breakers were

Table 12.4: Interfacing components used in the Jamupani energy system.

Component	Quantity	Part details
`Rectifier`	1	TDK Lambda CUS 15000M-36
`Charge controller`	1	Coleman Air C400-HVAD hybrid charge controller
`Dump load`	1	Coleman Air L1000W24V
`Inverter`	1	Luminous Cruze+ 2.5 KVA
`Diodes`	2	Vishay VS-85HF
`Circuit breakers`	3	2 x 80 A Truck Star & 1 x 120 A Truck Star circuit breaker

chosen to go between the PV system and the charge controller. Between the battery bank and the charge controller, a $120A$-rated Truck Star circuit breaker was selected.
Table 12.4 summarises the components needed for the interfacing architecture.

12.4 Power distribution

A comprehensive distribution system was needed to channel the power output from the inverter to the different load lines in the village. Connections were needed for the school, the streetlights and to each of the 12 households. Jamupani is quite sparse with long relatively long distances between houses, and some dwellings are situated on the other side of the stream as well. Hence, multiple power distribution units (PDUs) were considered necessary.
The design of the distribution system is shown in figure 12.5, along with the different cable thicknesses needed for each section. As per the design, power flows from the inverter to a central PDU, where the main load management controller would also sit. From here, the school primary and secondary lines are supplied directly. Two separate connection are provided for the households and streetlights. Both sides of the Jamupani stream would be connected by their own PDUs (two on the school-side of the stream,and one on the other side)., and the auxiliary load management controllers would be installed at these PDUs. The layout of the distribution grid was based on a satellite image of Jamupani, as shown in image 12.6. One of the buildings belonging to the government residential school was chosen as the installation site for the PV system, the battery bank and the central PDU. This building is one of the teachers' dorms, and was thus considered a safe location for the electric equipment. Further, the building is somewhat far off from the rest of the school premises, and hence it is unlikely that the pupils would get to the equipment.
From the central PDU, four different connections would be drawn, two to the school and one to each side of the Jamupani stream. One of the school lines would be connected to all of the school buildings, and one to a socket at the school main office. Each secondary PDU would be installed into households in Jamupani. For this, houses of the school staff were selected. On the school side, nine households and four streetlights would be supplied, and on the other side, three households and the rest of the outside lighting would receive connections.
Overhead distribution lines were selected to supply power to Jamupani. Due to the sparseness of the village, approximately $3.5km$ of overhead wiring would be needed to reach all target

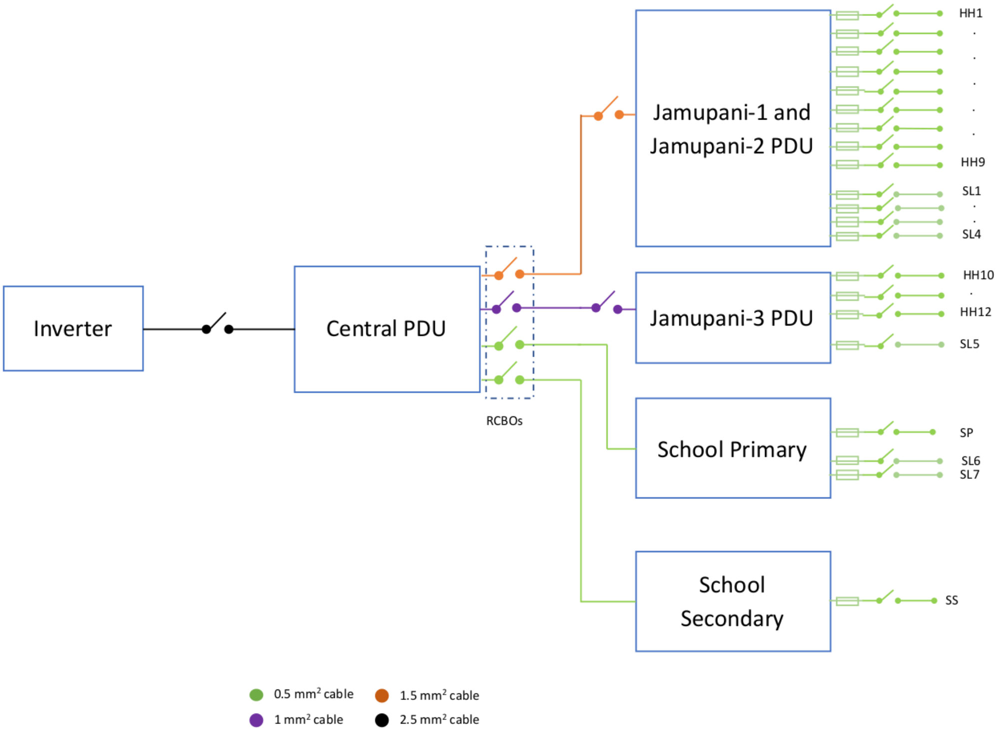


Figure 12.5: Distribution system design[93].

buildings. The longest wire would span $400m$ to connect the control room central PDU with the Jamupani-3 PDU on the other side of the stream.

Wire sizing and selection

The wires needed to be carefully selected based on the power rated for each section of the Jamupani microgrid. Choosing too thin wires would cause them to break or melt, leading to power outages and a fire hazard. Wires are also very expensive, and the thicker they are, the pricier they become. Oversizing them would hence pointlessly bring up the energy system's capital cost. To size the wires correctly for long-term use, their maximum rating should be chosen as greater than the maximum current along the line as per the design. Table 12.5 shows an example of how the maximum current rating relates to the wire conductor cross section as defined by the American Wire Gauge (AWG) system[94]. The second requirement for the wires was the voltage drop along the lines. The voltage drop along the length of any given line was to be maintained at five per cent of the input voltage[95]. The voltage drop depends on the current flowing through the wire as well as its length as follows:

$$\Delta U = \frac{2I_{max} l}{kq}, \tag{12.1}$$

where ΔU is the voltage drop along the line, I_{max} is the maximum current through the wire, l is the length of the line, k is the electrical conductivity of the given conductor material in $\frac{m}{\Omega mm^2}$, and q is the cross-sectional area of the conductor is mm^2.
The lengths of the wires needed for Jamupani were calculated based on the satellite imagery

Figure 12.6: Distribution system layout[93].

Table 12.5: American Wire Gauge system for selection of wire thickness.

Wire gauge (AWG)	Conductor cross-section (mm^2)	Rated current (A)
1	42.4	119
2	33.6	94
3	26.7	75
4	21.1	60
5	16.8	47
6	13.3	37
7	10.6	30

Table 12.6: Specifications of chosen distribution cables.

Dimension and type	Total length (m)	Selected cable
$0.5mm^2$ 3-core insulated	2500 m	Havells Cable WHMFDSKB3X50
$1.0mm^2$ 3-core insulated	400 m	KEI 3-core cable
$1.5mm^2$ 3-core insulated	300 m	Havells Cable WHMFDSKB31X5
$2.5mm^2$ 2-core insulated	400 m	Havells Cable WHMFDSKB22X5

available from the village. Based on the length and maximum current of each section of the energy system, the voltage drop, and subsequently the right thickness of the wires were computed. Based on these calculations, in was determined that the Jamupani microgrid would need a combination of $0.5mm^2$, $1mm^2$, $1.5mm^2$ and $2.5mm^2$ wires.

Based on the computed specifications, high-quality wires available on the Indian market were selected. An added requirement was that the overhead cabling would be outside and thus exposed to weather, and possible damaging. Table 12.6 gives the details of the chosen wires. Apart from the distribution cables, small quantities of specialised cables were needed to connect some of the interfacing components due to the high current ratings between the power sources and the charge controller, and between the charge controller and the battery bank. In the former case AWG 7 wires were used, and in the latter, AWG 2 cabling was necessary.

12.5 Safety considerations and training

One of the main objectives of the pilot sustainable energy system was to ensure its robustness, safety and user-friendliness. Hence, throughout the design phase, a lot of attention was given to the aspect of operational safety. In the following, the main safety measures of the system are discussed in detail.

Grounding and lightning protection

The entire energy system was designed to be grounded at a single point to avoid issues with ground potential difference. The ground of all connections and the earthing of exposed conductive parts of components would need to be connected to a potential equaliser. A separate grounding wire of $16mm^2$ cross-sectional area would be connected to a copper plate, and the plate would be installed 1.5 meters under ground. Additionally, the area in the direct vicinity of the copper plate would have to be filled with earthing salt to decrease the resistivity of the soil.

The grounding configuration planned for Jamupani is the TN-S system, in which the neutral line is grounded very close to the power source. In the Jamupani grid, the grounding point would be right after the inverter.

As Jamupani is located in the mountains, the village is not very susceptible for lightning striker. However, for added safety, a lighting resistor was to be installed at the control facility where the PV system, battery bank and central PDU would be installed. A 2-meter metal rod would be installed on the roof of the building, with a conductor wire of $16mm^2$ connecting it to the potential equaliser. Figure 12.7 shows a schematic of the designed grounding system.

Overvoltage, short-circuit and open-circuit protection

Various components were used to protect the Jamupani microgrid against overvoltage, short-circuit current, and open-circuit protection. The central components would be a residual current-operated circuit breaker with overcurrent protection (RCBO). One RCBO would be installed for each distribution line (see figure 12.6). Additionally, miniature circuit breakers (MCB), were to be installed for overvoltage and short-circuit protection, along with simple switches that could be easily used manually in case of emergency. The RCBOs, MCBs and switches were all selected based on the maximum currents calculated for each section of the energy system.

As an added safety feature, all the household and streetlight connections were to be protected

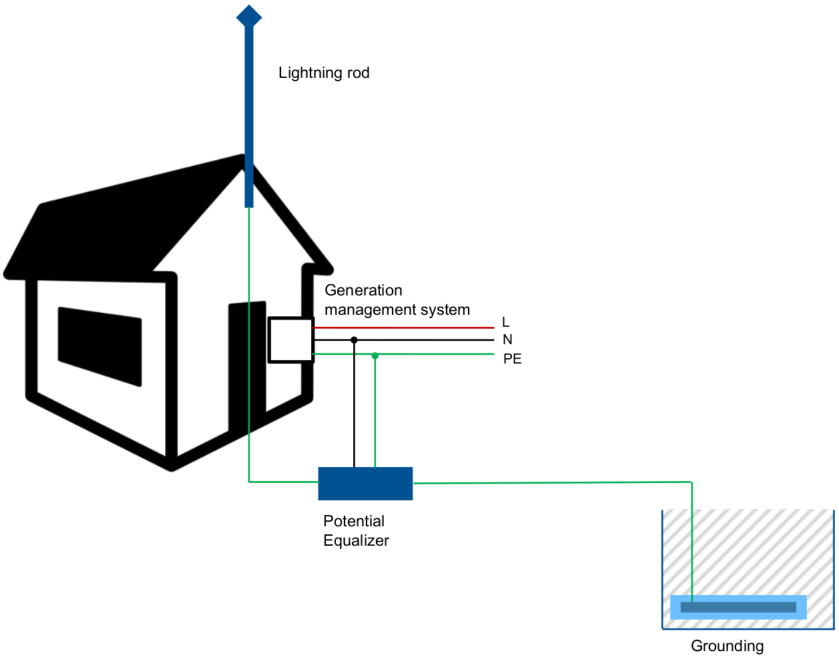


Figure 12.7: Schematic of grounding system with lightning arrestor.[93].

Table 12.7: Safety components for Jamupani microgrid.

Component	Quantity	Details
`RCBOs`	4	Hager AD206Y, 6 A rated
`MCBs`	2	Schneider Acti 9
`Fuses`	15	PTC fuse, 0.4 A rated

by PTC fuses installed at the PDUs. Table 12.7 summarises the safety measures against overvoltage, as well as short and open circuits.

Other safety considerations

Safety was considered in the selection of the distribution cables. Solely multi-core wires resistant of fire were chosen, and IP68 rated connectors were selected to protect the cabling against the elements. The lines were to be installed high up on poles to minimise unwanted human contact, and the line sag was to be kept minimal.

Additionally, a fire extinguisher was to be installed at the control room in case of emergency, and buckets filled with sand would be distributed around the village. To further reduce the risk of fire, all components were to be installed with sufficient spacing between them to allow for heat dissipation.

As the villagers of Jamupani have little previous experience with electricity, it was considered essential to train them to use it safely. For this purpose, a training session was designed to be given to all villagers on which appliances could safely be used with AC power, how to troubleshoot problems and how to react in case of emergency. Additionally, based on the suggestions of the headmaster of the Jamupani school, two villagers were selected to be trained to operate and maintain the system. These people would be involved throughout the installation of the energy system, from civil work to electrical wiring. Further, they would take part in the testing of the system to gain more experience in how it operates. Finally, they would be given a formal training session, during which they were trained on the following:

- operation of Jamupani microgrid
- difference between DC and AC power
- how to inspect micro-hydro turbine, from stream inlet to turbine
- how to inspect and clean PV panels
- how to measure PV panel voltage
- how to inspect battery acid level
- detection and troubleshooting distribution and electrical faults
- detect faults in controller PCBs and replace PCBs
- operation of CO_2 fire extinguisher
- how to replace fuses

This list is not exhaustive.

Chapter 13

Implementation of Jamupani microgrid

The designed pilot energy system was installed in Jamupani between April and July 2019, by two TUM master students with the help and support from a local NGO, Further & Beyond Foundation, as well as from a very committed local leader, Anjite Menjo. Several volunteers of the NGO took part in the installation process, and many of the villagers and school staff were involved as well.

Prior to the installation, the NGO had obtained an official permit from the government, and the disctrict commissioner promised that the system would be taken over by the local government once successfully installed.

The installation of the renewable microgrid of Jamupani was a difficult and lengthy process. Due to delays in the shipment of some of the key components, the installation had to be carried out in the rainy season, in the worst of conditions. Several days were lost due to landslides and shortage of goods. Jamupani has no reliable mobile connectivity and no internet, so problems had to be troubleshot off-line and with limited hardware. As will be discussed in the rest of this chapter, many design changes were necessary due to local conditions, device malfunction, and wrong assumptions taken in the design phase.

Despite the challenges, the installation was completed successfully, and the system was handed over to the local government. The Jamupani microgrid has been running without fail for over eight months at the time of writing.

This chapter will give a comprehensive overview of the installation process of the sustainable energy system pilot, as well as the design changes realised throughout this process.

13.1 Logistics

Jamupani's location in the mountainous jungle of Arunachal Pradesh makes it a logistical challenge to transport any goods to the village. The only manner to reach it is by a narrow foot trail through the jungle, a journey of 1.5 hours from the nearest seasonal road. The path is narrow and steep, and connected in laces by hand-made bridges not designed for heavy loads. However, to install the hybrid microgrid, over $3000 kg$ of material needed to be carried to the village. The components and material were transported with lorries to a nearby village, from

Figure 13.1: Logistics involved in the Jamupani microgrid installation.[93].

where on they were carried on foot by the TUM team, volunteers, villagers and porters from nearby villages. Figure 13.1 shows how laborious the work of carrying the materials was.

13.2 Installation of PV system

The PV system was installed on the South-facing roof of one of the staff dorms at the Jamupani school premises. The PV panels were connected to the combiner box in parallel, and fixed in place with a metal frame. The wires MC4 connectors were used to connect the wires to the combiner box for added safety. The combiner box was then connected to the charge controller through a single output. Finally, the metal bodies of the PV panels were connected to the potential equaliser via an earthing cable. Figure 13.2 shows the PV system during and after installation.

13.3 Installation of micro-hydro system

Installing the micro-hydro system was one of the tasking phases of the whole system implementation. A significant amount of civil work was needed, and the following sections discuss the steps in detail.

Site selection

Before installation, a suitable site needed to be selected. The operation requirement for the turgo turbine, as per section12.2, was to generate a head of $20m$ minimum. The site identified based on satellite imagery of the Jamupani stream could have easily generated the necessary head, but based on the villagers' experience, this location is very prone to flooding which could damage the turbine of the pipe system. Hence, a new location had to be found.
Based on the suggestion of the villagers, a site near the school grounds was inspected. The

Figure 13.2: PV installation on the control room rooftop.[93].

Figure 13.3: The penstock location as per the original design (red), and the new location (white).[93].

measurement of potential head was carried out using a level water tube, a spirit leveler and a large scale[96]. With this method, a location wit a total head of $25m$ was found, at a distance of $170m$ from the stream. Figure13.3 shows the original penstock location in red and the new location in white. Moving the hydropower system away from the Jamupani stream caused the length of the penstock pipe to change from $123m$ to $170m$. The increase in length also increased the friction losses within the pipe, leading to a lower power output of the turbine.

Figure 13.4: Intake tank.[93].

Further, moving away from the stream also increased the length of the intake pipe from the stream to the intake tank. The new length of the intake pipe was measured to be $90m$.

Construction of intake tank

The intake tank is an essential part of the hydropower system as it causes dirt and sand to separate from the water, and ensures a bubble-free stream of water through the penstock pipe to the turbine. Based on the Vinci Aqua turbine manufacturer's instructions, a tank of approximately $1.7m^3$ was built. Additionally to the connections to both the intake and penstock pipes, a drainpipe was fitted that could be opened to remove sedimented debris, and an overflow pipe was provided to mitigate problems due to flooding. Figure 13.4 shows the finished intake tank. For the construction of the tank, around $3000kg$ of sand and gravel, and $500kg$ of cement were required. The sand was carried manually from the from the stream and the Ithun river, which flows $0.5km$ away from the installation site. The concrete was used to build a foundation for the tank, and the tank base and walls were strengthened with reinforced steel rods. Additionally, the tank inner walls were plastered to minimise leakages, and the tank was close at the top with tin sheets to avoid debris.

Piping

Based on the measurements from the new location, a total of $170m$ of penstock pipe was needed. The rubine manufacturer instructed to use high-density polyethylene (HDPE) pipe of $75mm$ diametre. The pipe needed to handle the pressure of $25m$ head, and thus PN4 ($4\frac{kgf}{cm^2}$) were needed. A supplier for the required pipe was found in Siliguri, India.

Due to the lacking infrastructure and availability on the market, large sections of the pipe could not be delivered to Jamupani. Hence, multiple 20-foot-long sections were chosen, and the full length of the pipe was constructed with joints tightened with clamps. The penstock was connected to the nozzle of the turbine and the intake tank through a heat-treatment process, and the connections wree strenghtened with mechanical clamps. To avoid damage of the penstock pipe, it was fixed inplace with locally available materias such as stones.

The intake pipe connects the stream to the intake tank. Based on earlier measurements, $90m$ of pipe were needed, with a diameter of $75mm$, as per the instructions of the turbine manufacturer. To protect the hydropower system from damages during the rainy season, a strong galvanised iron pipe was chosen as the intake pipe. Multiple 20-foot-long sections of intake pipe were joined together to achieve the required length.

At the point where the intake pipe was connected to the Jamupani stream, a pool was constructed. The mouth of the pipe was protected from debris by installing a filter and mesh structure in front of it, and the point of connection was fixed with cement.

Due to the uneven terrain, negative head was a potential problem in the penstock pipe. Negative head means negative pressure building inside the pipe if in any section the water flow climbs up instead of going down steadily. Negative head creates losses that decrease the total head, and had to be dealt with to improve the power output of the turbine. This was carried out by making the pipes straight with no bending, and by removing any obstacles that would force the pipes to rise up.

Installation of turgo turbine

The Vinci Aqua turgo turbine was installed onto a concrete platform to avoid any vibration during operation. A channel was made into the platform to channel the water flowing through the turbine back to the stream, and an enclosure was built around it to protect the turbine from the elements, and to keep unauthorised people away. To make the output water flow smoothly, the platform was raised to increase the clearance of the turbine from the ground.

The nozzle of the turbine was connected to the penstock pipe as described previously. The nozzle also has a fate valve to turn off the water inflow in case of maintenance of emergency. The output power of the turbine was connected to the rectifier residing in the control room, 200 meters away. For this, the 2-core $2.5mm^2$ wire was used. Figure 13.5 shows the finished turbine installation in operation.

During testing, it was found out that the turbine could only produce around $260W$ at its chosen location. This reduction in power is mainly due to the extremely long penstock pipe length, causing substantial pressure losses and decreasing the dynamic head. Indeed, a dynamic head of only $14m$ was measured, causing the turbine to produce a fraction of its rated $1kW$. A better location was looked for by placing the turbine temporarily to other promising positions along the stream, and testing its output. No better location was found where the turbine would not be dangerously close to the stream, and so the system was left as is. This meant that the total power output of the energy system would be significantly lower than anticipated, and called for changes in the original design. A summary of all design changes is given in the following section. A schematic of the micro-hydro system at its final installation site is given in figure13.6. Due to the low power generation of the turbine, it could not be connected to the charge controller as the turbine had no internal power limiting device. Thus, when connected,

Figure 13.5: The turgo turbine after installation.[93].

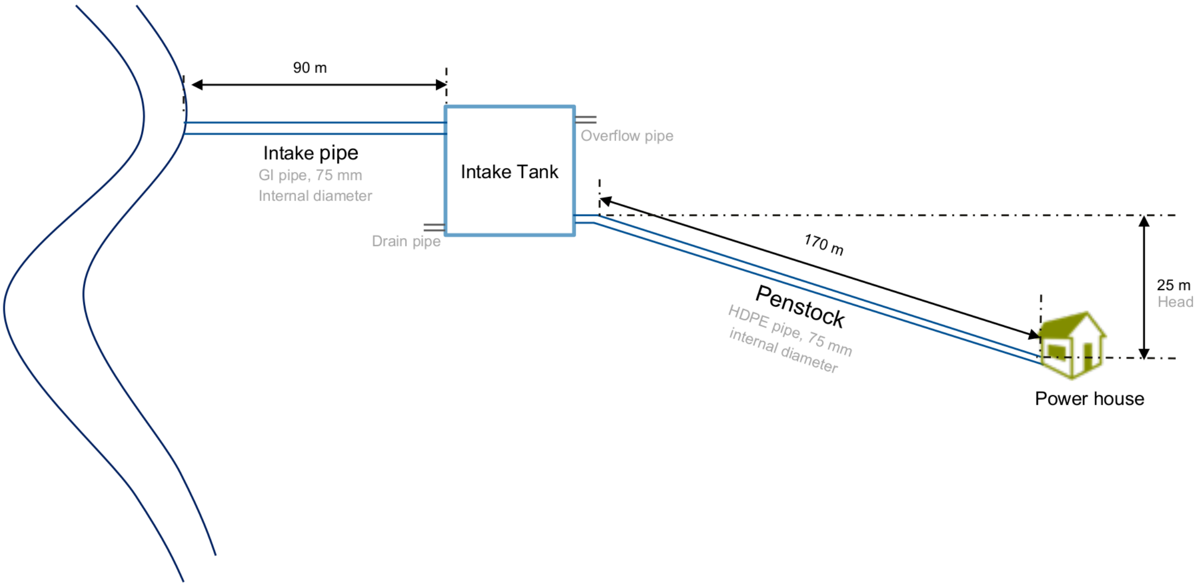


Figure 13.6: Schematic of the full micro-hydro system.[93].

Figure 13.7: Interfacing components and battery bank installed into the control room.[93].

the turbine would try to provide its maximum rated power to the battery bank, and stall. A power limiter had not been considered a necessity in the design phase as it was still assumed that the turbine would operate near its maximum capacity. When the problem was discovered, it was impossible to obtain new components due to the remoteness and non-existent connectivity of the village. Hence the decision was made to separate the PV and micro-hydro systems. This had a major effect on the load management system, but the end users would notice little difference in the functionality of the microgrid.

13.4 Installation of interfacing components and battery bank

The interfacing components and the battery system were installed into the control room, onto the roof of which the PV system had been fixed. The components were mounted on a shelf with clamps to avoid movement, and the batteries were placed on the floor underneath the shelf. Both the central PDU and the main load management controller were placed into the control room as well. Figure 13.7 shows this setup. Further, the control room was separated from the rest of the building with a door an indicated with a number of warning stickers. This was a measure to keep unauthorised people out of the room.

13.5 Installation of load management system

As detailed in section 13.3, the microgrid layout needed to be changed due to the low power output of the installed micro-hydro turbine. The energy system would no longer work as a pure hybrid as the PV and micro-hydro power generation had to be separated. Figure 13.8 shows the system after the design change. As seed in the new layout, the micro-hydro turbine was separated from the PV system, and would fully supply the school. This decision was made as the power production of the turgo turbine was enough to cover the continuous load of the school even at reduced capacity. The secondary line for laptops had to be disconnected but

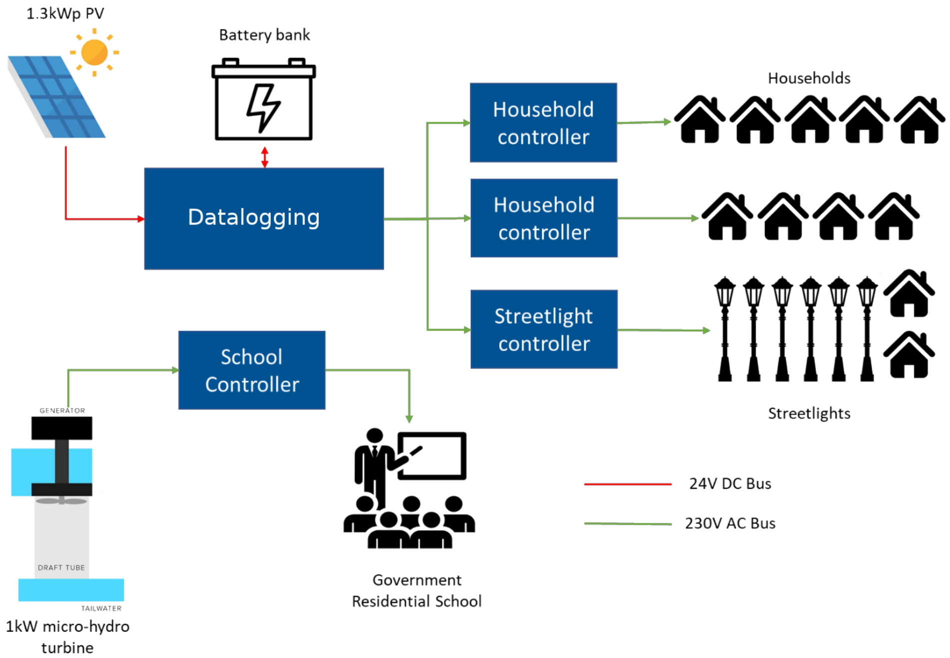


Figure 13.8: Changes made to the layout of the microgrid and the control system.[90].

could be reconnected in the future if the turbine power output increases. The PV system would then be used to supply the streetlights and the households with power. The battery bank would be charged by the produced PV power during the day, and cover the peak load that occurs after sundown.

Besides the alterations necessary in the microgrid design, changes had taken place in the demographics of Jamupani since the initial energy needs survey. The households on the farther side of the Jamupani stream had separated into their own village, and had received a 300W solar panel each[1], and thus did not wish to be connected to the microgrid. This reduced the number of households to nine.

Based on these changes, the original load management system design as per section 8.1 also needed to be changed. Instead of having one main controller and several auxiliary controllers controlling the whole microgrid, a separate school controller would now be responsible for controlling the micro-hydro turbine and the school load. Dedicated household controllers would control the power input to the majority of the households, and a third controller type would take care of controlling the streetlights[2]. The following sections discuss the operation logic of each controller in detail.

School controller

The original main controller was reprogrammed into the school controller for the new microgrid design. Based on the new maximum capacity of the hydro turbine, the school consumption

---

[1] The inhabitants of this new village, New Chetani, had received the solar panels from the government based on the fact that, unlike Jamupani, this new village had never officially been electrified.

[2] Additionally, two households only wished to use electric light, and where thus connected on the same line as the streetlights.

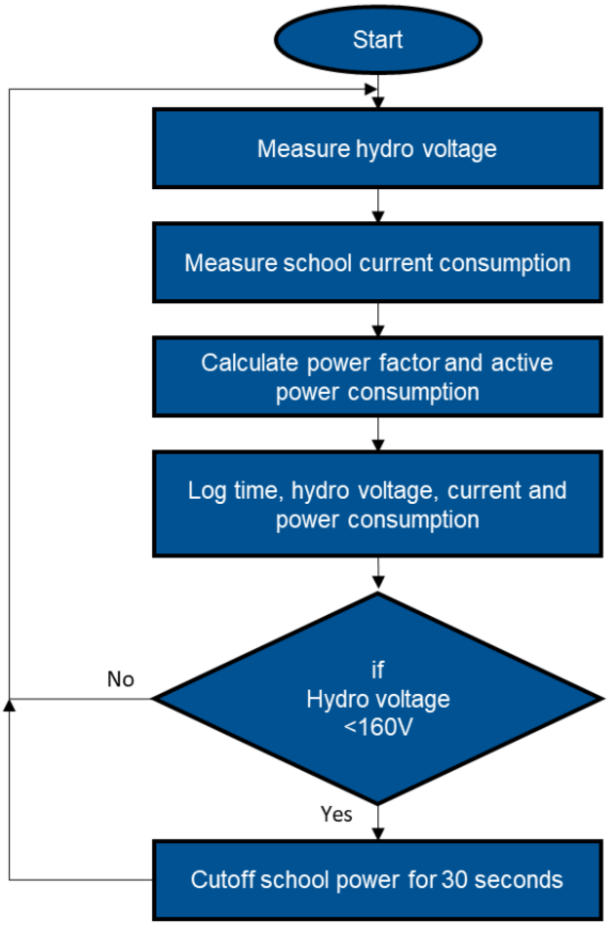


Figure 13.9: Logic flowchart for the school controller.[90].

was limited by the controller to $260W$. The power would be cut off for 30 seconds each time this limit was exceeded. Additionally, the controller needs to log voltage, apparent current, power factor and active power consumption because the turbine is no longer connected to the central datalogging device. The logic flowchart of the new school controller is shown in figure 13.9. The school controller measures current with a $5A$ rated Hall sensor. An RCBO is used to protect the controller and isolate it in case of faults.

Household controller

The household controller provides power to the connected households between 18:00 and 23:00, and limits each household's power consumption to $60W$. If this limit is surpassed, power is cut off for 30 seconds and then automatically restored. Additionally, the household controller logs voltage, apparent current, power factor and active power consumption for each connected household. The logic flowchart for the new household controller is shown in figure 13.10. Household current is measured with a shunt resistor and a differential amplifier, and fuses are used at every household line to protect the controller and the rest of the energy system in case of faults.

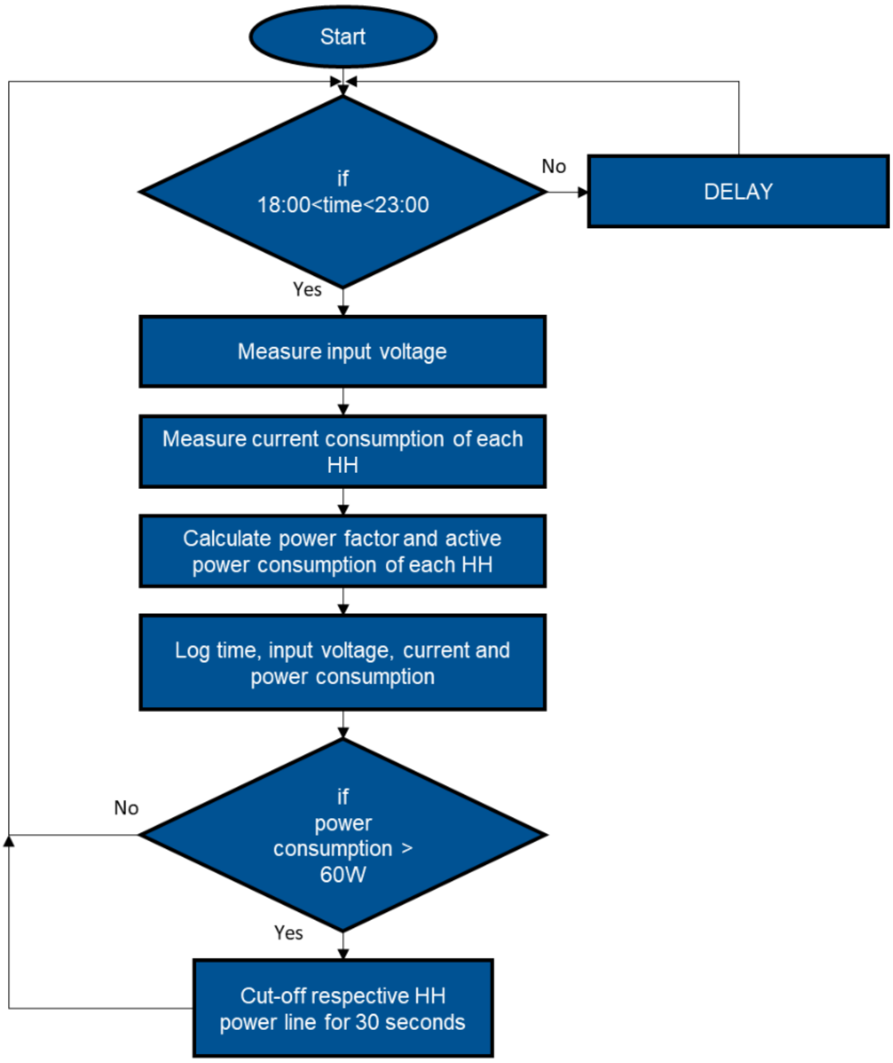


Figure 13.10: Household controller flowchart.[90].

Streetlight controller

The streetlight controller is responsible for powering the outside lighting and the lights of two households from 17:00 to 23:00. Further, it logs voltage, apparent current, power factor and active power consumption. As in the case of the household controller, a shunt resistor and a differential amplifier is used to measure current on each line. Figure 13.11 shows the logic flowchart of the controller. As the controller only has five output pins, multiple of the $25W$ streetlights had to be connected in parallel one output. The two households receiving power on this line are also connected in parallel with one streetlight each, and hence the lines' maximum allowed power consumption was set to $90W$. If this limit is exceeded, the power is cut for 30 seconds.

Each of the controllers were implemented onto a two-layer PCB, with the sensors, Arduino platform, control relays and power supply on the same PCB. Figure 13.12 shows the finished layout of a household controller PCB.

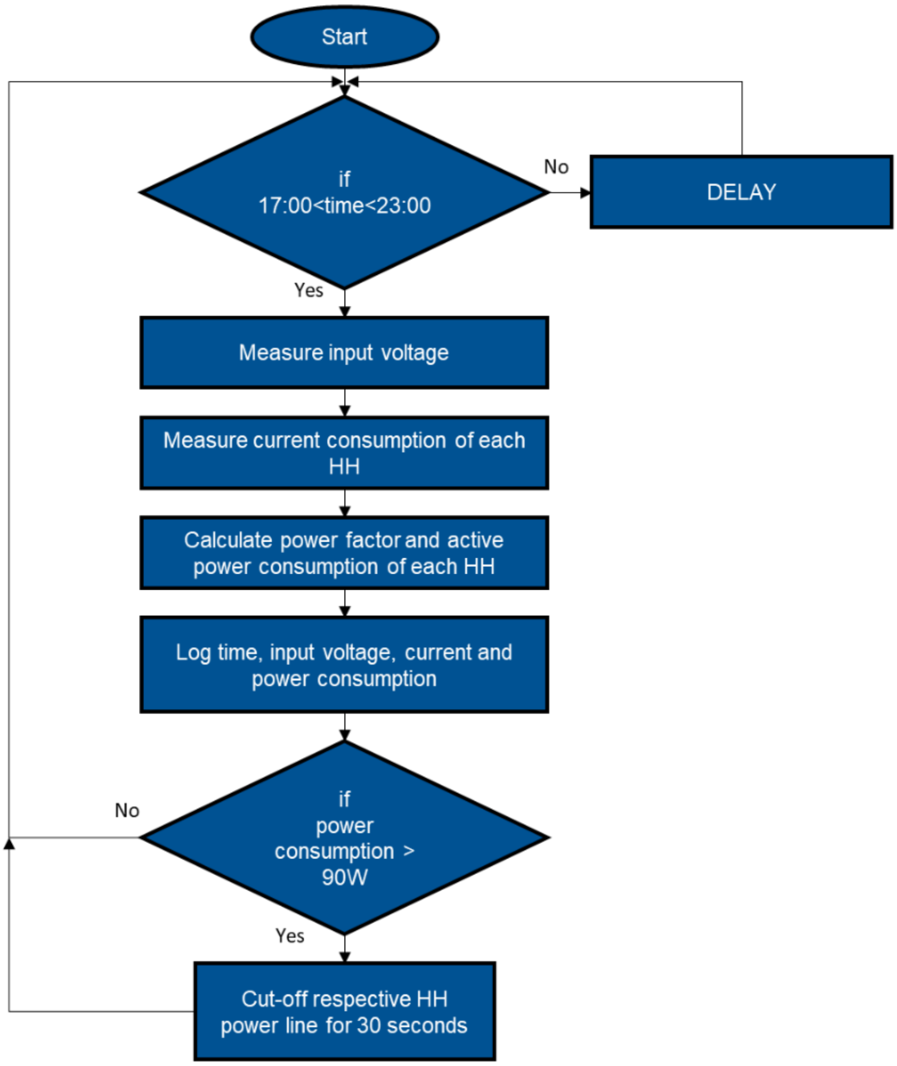


Figure 13.11: Logic flowchart for the streetlight controller.[90].

13.6 Power distribution

The final deployment of the distribution system for Jamupani deviated significantly from the original design. The major reason for this is that the farther side of the Jamupani stream had separated into its own village and did not wish to be connected to the microgrid. Further, between the initial survey of 2018 and the installation, new families had moved to Jamupani, and needed to be connected as well. Two households in the village are homes to elderly people that only wanted access to electric lighting. These households were to be connected onto the streetlight line. Taking all these changes into account, a new distribution layout was creates, as seen in figure 13.13. The overhead cabling was mostly realised by reusing old electrical poles that had been left standing after the failed attempt by the government to electrify Jamupani in the early 1990's. All of the connections of the PDUs in the village, the households themselves, and the school could be routed through these unused poles. In one location,

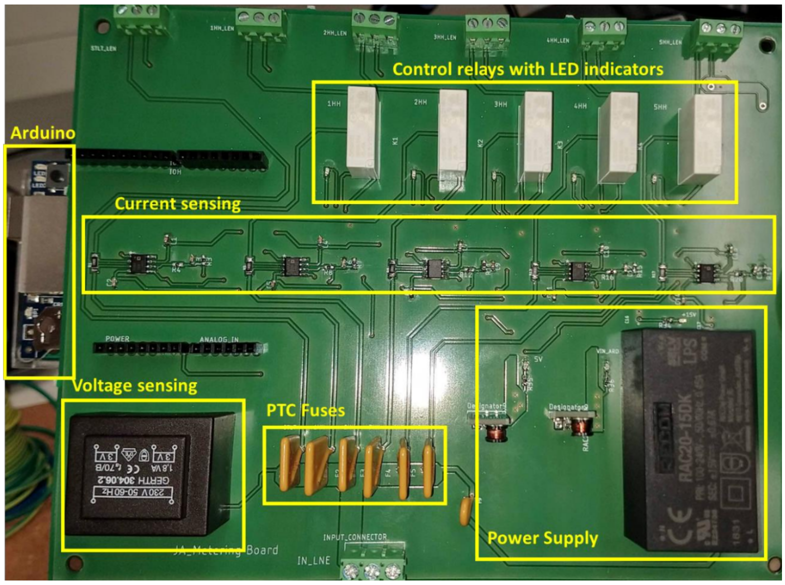


Figure 13.12: The PCB layout of the household controller.[90].

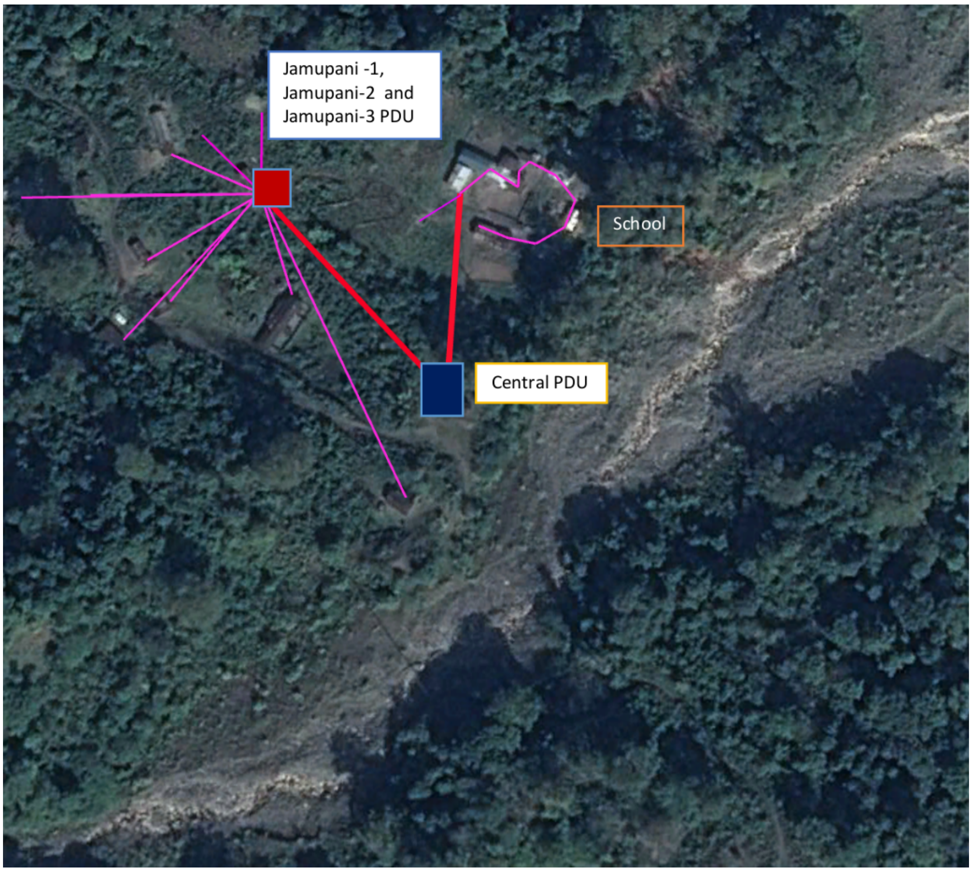


Figure 13.13: New layout for power distribution.[93].

Figure 13.14: Installation of overhead cables.[93].

an additional wooden pole was used to minimise sag in the distribution line. Figure 13.14 shows the installation process of the overhead cables. Each household received two LED bulbs, two bulb holders, along with switches and sockets for their appliances. The school buildings were also equipped with LED lighting and the necessary holders, switches and sockets. These components were connected to the distribution lines through box or junction connectors, effectively separating the internal wiring from the distribution line. This ensures that the internal wiring remains undamaged even if the dirstribution cable is pulled down by a falling tree or due to an accident.

$0.5mm^2$ three-core cables were used for internal wiring. The wires were placed near the ceiling to avoid unwanted human contact, and fixed with clamps. Sockets and switches were mounted on the walls, high enough to be out of reach of children. For each connection inside a household, a switch was provided, ensuring that there is always an option to quickly switch off power manually if needed.

The original system design included seven streetlights but as the opposite side of the Jamupani stream was not connected in the end, only six streetlights were needed. The remaining light would then be used as a spare part. Three of the streetlights were installed at the school premises, and the remaining three in the village itself. All the lights were connected to one PDU, along with the two households that only needed electric lights.

The streetlights were clamped to metal rods that were subsequently attached to the electrical poles used for power distribution. The villagers' opinion and instructions were sought to place the lights where they were needed the most.

13.7 Installation of safety features

For the safety and robustness of the Jamupani microgrid, several safety features had been added to the system design. All of the designed features were successfully installed into the energy system, and the villagers were consulted throughout to understand how to take into

Figure 13.15: Installation of the lightning arrestor and the copper plate.[93].

account local habits.

Lightning arrestor and earthing system

A two-meter lightning arrestor was installed on the rooftop of the control room. It was fixed with metal clamps and insulated where it could otherwise come into contact with conducting materials. A $16mm^2$ conductor cable connects the lighting rod to the ground.

All of the earthing lines from the conducting microgrid components were connected to a potential equaliser as explained in section12.5. The neutral and ground lines of the microgrid, tapped to after the inverter and before the RCBOs, were also connected to the potential equaliser, and it was then connected to the ground with a $16mm^2$ cable. The connecting cable leads to a $1m^2$ pure copper plate placed at a depth of more than one meter underground, and surrounded by a mixture of salt and charcoal to reduce the resistivity of the surface. A metal conduit was used to protect the section of the connecting cable that runs underground. Figure 13.15 shows the installation of these safety measures.

Other safety measures

Miniature circuit breakers (MCB), residual current-operated circuit breakers with overcurrent protection (RCBO) and switches were installed for the added safety of the energy system. MCBs and high-current switches were connected between the power supplies and interfacing components, and to the inputs and outputs of the charge controller. RCBOs were fitted to the inverter output and into the distribution lines. The MCBs and RCBOs were mounted on DIN rails inside the control room. The high-current switches were places there as well.

Power distribution safety was ensured by placing the cables out of reach of the public, and by minimising sag in the cables. The villagers and the school staff were consulted to place the wires in the safest location possible. This included minimising human contact and possible

Figure 13.16: Safety installation. From the left, RCBOs, IP68-rated wire connectors, warning stickers and fire extinguisher.[93].

damage through falling trees etc.

All of the distribution lines were connected with IP68-rated wire connectors, protecting the connections from rain and dust. The same connectors were used for the streetlights, and the joints between the distribution cables and the internal wiring were protected by using box or junction connectors. Further, the internal wiring was laid in a manner to minimise joints to avoid joint breakage. Each family was consulted to find the safest passage for the wires in every household.

The microgrid components were made visible by placing colourful warning stickers on or near the components. Further, free access to safety-critical devices and areas such as the micro-hydro turbine or the entire control room was restricted by enclosing them, and made visible by adding warning stickers on the doors.

Fire safety was enforced by placing buckets of sand around the village, and instructing the villagers on how to use them. A fire extinguisher was installed in the control room, and individual electrical components were placed at a proper distance from each other to avoid overheating. Figure 13.16 shows some of the installed safety measures.

Chapter 14

Discussion

The sustainable microgrid pilot project was installed in Jamupani, Arunachal Pradesh between April and July 2019, with the help of the local NGO, Further & Beyond Foundation, and a dedicated local leader, Anjite Menjo. Many of the components were donated by Indian companies, and the villagers of Jamupani were strongly involved in the installation process. Despite careful design, the changes in village demography and the challenging circumstances of the deployment process caused substantial changes in the system. The installation was carried out in the rainy season, and there was neither mobile nor internet connectivity in the village, making troubleshooting difficult and forcing the team to take decisions based on limited knowledge.
However, the installation was completed successfully, and is capable of providing the government residential school and the villagers of Jamupani with power as planned. The school receives a continuous supply of $260W$ from the micro-hydro turbine, and the villagers obtain $60W$ daily, from 18:00 to 23:00. Additionally, two villagers were trained to operate and maintain the microgrid. They were also provided with training manuals and tools required for the tasks.
After completing the installation, the Jamupani microgrid was handed over to the local government, which will be responsible for the costs of maintaining it. As of now, the microgrid has been operational for over nine months. No issues have been reported.
In the rest of this chapter, the major changes to the original microgrid design will be summarised. Subsequently, the steps taken to train and to support the Jamupani community will be discussed. Then, the details of the system handover to the local government will be explained, and finally, some suggestions for the future improvement of the microgrid will be provided.

14.1 Major design changes

As detailed in the previous chapter, multiple things led to the need to change the original microgrid design. The major issue was that no location was found for the micro-hydro turbine where its maximum capacity would have been reached. The highest output was $260W$, which rendered it impossible to connect the turbine to the charge controller. The charge controller has no power limiter, and would try to extract the maximum capacity of $1kW$ from the turbine at all times, making it stall if insufficient power was available.
The demographics of Jamupani had also changed between the initial energy needs survey and the installation. New people had moved to Jamupani, increasing the number of households.

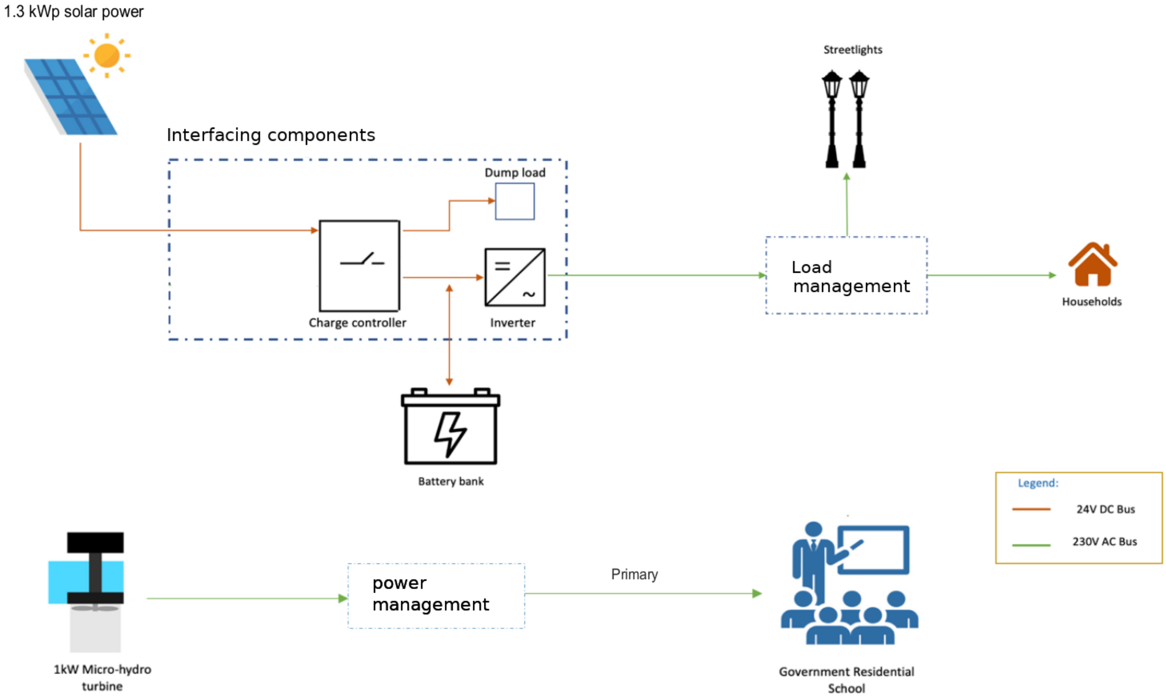


Figure 14.1: Final system layout of Jamupani grid.[93].

Further, the original design considered the electrification of both sides of the Jamupani stream, but one side had separated from Jamupani, and declared itself independent. Under its new name, New Chetani, this side was eligible for renewable energy subsidies from the government, and each household had received a $300W$ solar panel. Hence, they did not wish to get connected to the Jamupani microgrid.

The above factors forced the original design to be changed. The two power sources were separated, no longer forming a pure hybrid system. The micro-hydro now supplies the school, whilst the PV system and battery bank are used for the streetlights and the households. Hence, two separate AC lines are used to power the necessary loads. This substantially changes the load management system as well. Due to the modularity of the original design, it was easy to reprogramme the main controller and the auxiliary controllers into a designated school controller, household controllers and a streetlight controller. Figure 14.1 shows the final system layout as installed.And additional change due to the separation of the power sources was that no rectifier was needed on the micro-hydro line. This is simply due to the fact that the AC output of the turbine does not need to be rectified for the charge controller. Despite these substantial changes, the original goal of the system was achieved. The school, the households and the outside lighting receive the desired amount of power, with the exception of the school secondary line that was planned for laptop usage. However, this feature can still be added in the future if the turbine output increases. Table 14.1 summarises the major changes realised during the installation process.

Table 14.1: Summary of changes in the energy system design.

Original design	Installed microgrid
Hybrid microgrid system	Dual AC microgrid system
Micro-hydro nominal power output 600 W	Micro-hydro nominal output 260 W
Micro-hydro and PV system connected to charge controller. Both charge battery bank	PV system connected to charge controller and battery bank. Micro-hydro operates alone
Rectifier used to convert micro-hydro AC output to DC	Micro-hydro AC output used as is
Combined PV and micro-hydro power output supplies whole microgrid"	PV system supplies households and streetlights, micro-hydro supplies school
Load management through main controller and auxiliary controllers (distributed system)	Load management with independent school, household and streetlight controllers (peer-to-peer system)
Continuous power to school primary, and additional secondary connection supplied from 08:00 to 17:00	No secondary connection available at school
Seven streetlights to be installed	Six streetlights installed
Power to be provided to both sides of Jamupani river	Only one side receives power

14.2 Testing

After the installation of the Jamupani microgrid, all switches, sockets and bulb holders were tested to make sure no loose connections or short-circuits existed. Each component was of the energy system was tested first in isolation, and subsequently as a whole. After the completion of the installation phase, the system was monitored for several days to make sure no subtle faults were present.

The datalogger captured the system's data during the testing period as well, allowing for a deeper analysis of whether the system was supplying enough power. The school load and the output power of the micro-hydro turbine have been plotted in figure 14.2 over a period of one day. The plot clearly shows that the school load never exceeds the supplied power. The power output of the PV system was logged as well, and figure 14.3 shows how the solar production relates to the household load and the streetlights. On average, the PV system was producing around $3.9kWh$ per day whilst $1.5kWh$ was required by the households and the streetlights. The discrepancy between the peak PV production and the peak load was successfully taken care of by the battery bank. During the testing period, the maximum depth of discharge of the battery system was only 15.7 per cent. The test results clearly showed that the system was working as intended, and could easily cover the current power consumption of both the school and the village.

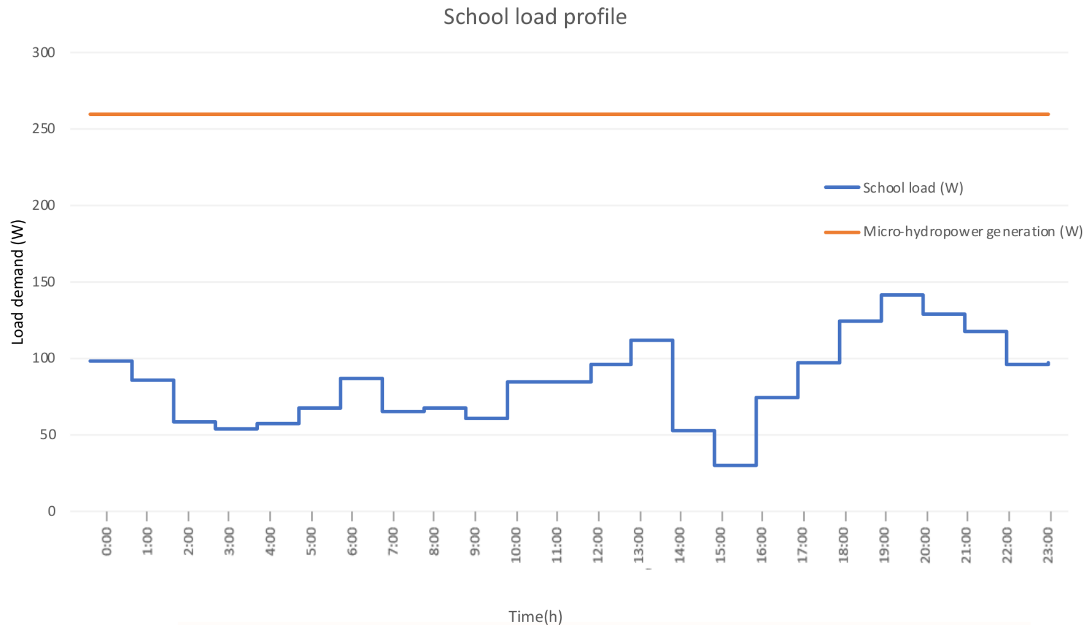


Figure 14.2: Micro-hydro power output versus the school load over 24 hours.[93].

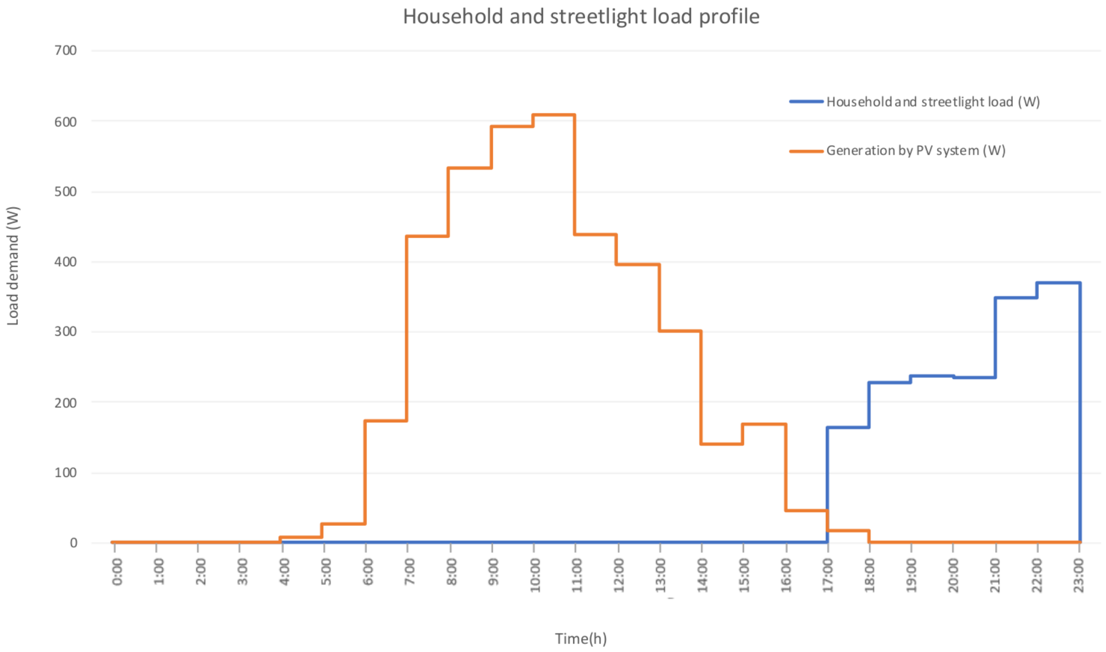


Figure 14.3: PV power production and combined household and streetlight load over 24 hours.[93].

Figure 14.4: Training and safety drills provided to the community.[93].

14.3 Community training and support

The main objective of the sustainable energy system pilot was to ensure its long-livedness by involving the community in its deployment, operation and maintenance. The villagers' experience and know-how was widely taken advantage of during the installation process, and their suggestions helped to adapt the system to their individual needs. All end users of the microgrid were consulted when installing the internal wiring, giving them the power to choose what was done with their homes. Additionally, the villagers' help was sought to place components in the safest locations possible, as showcased by the moving of the micro-hydro turbine from its original location.

To ensure the continuous maintenance of the system even in the absence of the TUM team, multiple members of the Jamupani community were involved in the installation of the system. This ensured that the villagers became familiar with the system, and would know how to troubleshoot simple issues such as blown fuses, cut wires etc. Further, it was decided to train two members of the Jamupani community to maintain the system for a small monthly pay. This money would come from the monthly fees payed by the users of the microgrid. Based on the suggestions of the school headmaster and the village elders, two villagers, Meleko Mega and Angijo Miso, were chosen for the training. Both of them were involved in the installation from the very beginning, including civil work required for the micro-hydro system, distribution and internal wiring, and the testing of the completed microgrid. Further, a formal training session was organised, where the design of the microgrid system was explained, along with the necessary troubleshooting procedures in case of faults. Section 12.5 explains the content of the training session in more detail.

After the training session, hands-on experience was provided by a practical session where all of the system components were inspected. Safety drills were also conducted and the chosen community members were instructed in the usage of the installed safety features. Figure 14.4 shows images of the training session. Furthermore, the school headmaster and the trained villagers were provided with a weekly and monthly checklist with which the microgrid is to be inspected and maintained. The list contains activities that improve the daily operation of the system and activities of preventive maintenance. These include removal of debris from the intake of the hydro-power system, the cleaning of solar panels etc. The full checklists may be found in appendix C. Additionally, each household in the village received an individual training session explaining hot to use the newly installed microgrid. This included informing them on which appliances are safe to use in an AC grid, how to safely change faulty light bulbs and other appliances, and on general safety procedures and best practices.

14.4 System handover

Before the installation process began, an official permission from the local government was sought and obtained. The government agreed to take over the system once installed and operational. Officially, it was decided that the Jamupani school would have the ownership of the energy system.

The formal handover took place after the testing and training of the community. The handover document was signed by the TUM team, the helping organisation Further & Beyond, the school administration, and by the sub-district officer. The sub-district officer is the most senior government official responsible for Jamupani and its vicinity.

During the handover, the sub-district officer announced that district commissioner had approved the plan to support the Jamupani microgrid by providing funds for its maintenance. Further, the sub-district officer signed an agreement with the village members to charge them ₹100 per month for using the microgrid. Additionally, the school agreed to pay ₹500 per month. The total amount would be used to pay the two trained villager members for maintaining the system.

As part of the handover procedure, the tools required to conduct maintenance tasks were donated to the school by the TUM team. Further, replacement components such as sections of the intake and penstock pipe, a large number of switches, sockets, bulb holders, fuses wires and LED bulbs were left behind. The aim was to ensure that the most common components could be replaces instantly.

14.5 Impact on community

Since the completion of the Jamupani microgrid in June 2019, anecdotal evidence of the positive impact of the system on the surrounding community has been obtained. As reported by the headmaster of the Jamupani governmental residential school, the access to electrical lighting has brought on a change in the curriculum. Some of the classes have been shifted to the evening, allowing the pupils to practise sports in the afternoon. According to the headmaster, the children are happier, and perform better on average, than before receiving electricity. Further, the school has now acquired a TV set and a satellite dish, making it possible for the pupils to follow educational programmes as per the national curriculum, and to watch entertainment in their free time. For a village with neither access to the cellular network nor the internet, satellite TV is the only connection to the outside world and hence not to be underestimated.

According to the accounts of the local leader, Anjite Menjo, who supported the Jamupani microgrid project throughout, the villagers of Jamupani are content with the functionality of the system, and no faults nor complaints have been reported to date. It is still unclear whether the energy consumption of the villagers has significantly increased in the course of the system's operation, and a thorough impact assessment should be carried out to determine this. Knowing how the energy consumption is evolving is essential to evaluate the need for future improvements on the system.

Shortly after the successful installation of the Jamupani microgrid, TUM's NGO partner Further & Beyond reported that one of Jamupani's neighbouring villages had expressed interest in implementing their own micro-hydro system. Some of the inhabitants of this village had actively helped in the installation of the Jamupani system, and now wished to obtain a microgrid for their own community. The TUM is not actively part of this new project but the Further & Beyond Foundation works together with the local government to realise it.

14.6 Conclusion and outlook

The sustainable energy system pilot was successfully installed in Jamupani despite some major changes to the original design. The success of the system was largely made possible by the thorough preparations preceding the installation. Utmost care was taken to identify and address possible barriers to renewable energy on technical, cultural and economic levels, and experienced local partners as well as community stakeholders were involved in the project to better understand the local needs and wants of the villagers of Jamupani. The community was consulted throughout the project, and the design was dynamically adjusted to better suit the local conditions.

In the end, a PV-hydro dual system was installed in Jamupani, with the PV-battery setup providing power to the village itself, and the micro-hydro turbine supplying the school load. Extensive safety measures were integrated into the system to ensure user safety and easy maintainability. Two community members were selected and trained in the operation and maintenance of the system, and they receive monthly remuneration for their activity as system managers. The villagers pay ₹ 100 per month to use the microgrid, and the Jamupani residential school pays ₹ 500.

The provided microgrid is fully operational but significant improvements should take place in the future:

Increasing micro-hydro power output

> The micro-hydro system only produces $260W$ of the maximum capacity of $1kW$ in it's current location. Therefore, the surrounding area of the Jamupani stream should be inspected to find a location where the power output could be improved. Creating the needed head artificially would be very laborious without access to heavy machinery such as excavators, and hence an unlikely option unless the local government provides Jamupani with a road connection.

Joining PV and microhydro generation

> For improved robustness and flexibility of the microgrid, the PV and micro-hydro generation should be joined through the charge controller as originally designed. Therefore, a power-limiting device should be installed between the turgo turbine and the charge controller to prevent the turbine from stalling at times of low power production. Alternatively, if the micro-hydro system was placed so as to ensure

maximum power generation at all times, the turbine could be connected to the charge controller directly.

Increasing household and school power allowance

In case the total power output of the Jamupani microgrid increases, the current allowance of $60W$ per household and $345W$ for the school should also be increased. This would allow for the villagers to use more appliances, and the school to introduce laptops as a form of teaching.

Conducting an impact assessment

To ensure the sustainability of the Jamupani system in the future, an extensive impact assessment should be realised. This would allow to see what changes have been positive for the community, and where adjustments are needed.

Improving datalogging and remote troubleshooting

Currently, the data gathered on the Jamupani microgrid is stored locally on SD cards. The SD cards are periodically taken to a town with access to the internet and sent over to the TUM for further analysis. By means of a satellite connection, or in case of improved mobile connectivity, the data could be automatically sent directly from the dataloggers with no human interaction.

As mentioned previously, the completion of the Jamupani microgrid has awoken interest in a neighbouring village to implement their own micro-hydro system. This can be seen as proof that the Jamupani microgrid has been successful, and that the local awareness of renewable energy has increased. It is also very promising that other villages in the region are willing and able to adopt renewable energy without outside influence. I hope that the Jamupani microgrid works as a catalyst, leading to the self-governed movement to electrify several villages in the region.

Chapter 15

Thesis conclusion

This doctoral thesis stems from the desire to understand and mitigate problems affecting the spread of renewable energy as a means of rural electrification. Its main goal was to create a pilot of a successful renewable energy project in rural India, showing that by determining the local barriers and taking them into account in system design and deployment, the sustainability and long-livedness of a rural microgrid could be guaranteed.

This report presents the research that was carried out in the process of identifying key factors that affect the advancement of renewable energy in rural areas, and concentrates on the topic of power quality as the main technical barrier. Keeping in mind the constraints posed by the energy system's rural application, two load management strategies were developed and compared to find a fitting solution to ensure that the end-users receive a stable power supply. Finally, with the knowledge gained through the research conducted as part of this thesis, a renewable-based microgrid was successfully designed and implemented in the village of Jamupani in Arunachal Pradesh, India. The microgrid was completed in June 2019, and at the time of writing, it has been operational for 10 months without fail.

Many of the lessons learnt during the Jamupani system design and deployment cannot, and should not, be generalised to apply to other renewable-energy systems as is. Instead, the reader should take note of the factors affecting the advancement of such systems, and thoroughly assess any target location in the light of these factors. There are no one-fits-all solutions to rural electrifications, and no shortcuts should be taken to implement a renewable energy project. That being said, several results of this project do bear broader significance. It cannot be stressed enough, that time needs to be invested into understanding the local energy demand, culture, and circumstances, and communication needs to be clear among all parties involved. Establishing trust between the target community and other stakeholders is key to successful implementation. Further, the technical design of a rural microgrid should be as modular as possible, so that in case plans change or components fail, the rest of the system stays operational, with or without alterations.

I sincerely hope that this report will serve other researchers and organisations working on sustainably electrifying those still without access to energy.

Appendix A

Energy need survey data

A.1 Nepal

S.No	Name	Age	Gender	Address	EL (outliers)	Marital Status	Economic Activitie
1	Ravi Prakash Upadhaya	24	1	Bhagyang	3	1	1
2	Prem Bahadur Shing	54	1	Bhagyang	0	1	1
3	Bir Kam Bahadur Shing	50	1	Bhajyang	1	1	1
4	Makar Bahadur Shing	53	1	Bhajyang	4	1	2
5	Dhanbire Bike (Dalit)	59	1	Bhajyang	0	1	1
6	Gede Bike (Dalit)	45	1	Bhajyang	0	1	2
7	Dhan Bahadur Nepali	60	1	Bhajyang	0	1	1
8	Nirmala Nepali	30	0	Bhajyang	0	1	1
9	Purna Bahadur Nepali	63	1	Bhajyang	1	1	3
10	Komal Kathai	35	1	Bhajyang	3	1	1
11	Ganesh Bahadur Shing	30	1	Bhajyang	3	1	2
12	Gorakh Bahadur Shing	56	1	Bhajyang	1	1	2
13	Lalit Ba. Shing	55	1	Bhajyang	1	1	2
14	Pushpa Devi Shing	33	0	Bhajyang	5	1	2
15	Binda Joshi Bajhal	34	0	Bhajyang	5	1	2
16	Rupmani Shing	37	0	Bhajyang	3	1	2
17	Harka Br. Shing	72	1	Bhajyang	1	1	2
18	Ramesh Wod	22	1	Bhajyang	4	1	2
19	Khadak Okhada	48	1	Bhajyang	2	1	2
20	Gagydher Asharki	46	1	Bhajyang	4	1	2
21	Karan Br. Okhada	43	1	Bhajyang	2	1	1
22	Keshav Wod	45	1	Bhajyang	2	1	2
23	Parwati Khati	28	0	Bhajyang	4	1	1
24	Sapana Khati	24	0	Bhajyang	4	1	2
25	Uma Khati	35	0	Bhajyang	0	4	1
26	Jain Ruda Khadaka	60	0	Bhajyang	0	4	2
27	Jay Laxmi Khati	29	0	Bhajyang	4	1	2
28	Ganga Devi Khati	37	0	Bhajyang	0	1	2
29	Sunita Khati	24	0	Bhajyang	0	1	1
30	Lal Mati Khati	58	0	Bhajyang	0	1	1

S.No	Name	Age	Gender	Address	EL (outliers)	Marital Status	Economic Activitie
31	Bal Bd. Gautam	52	1	Kavrepalanchowk	5	1	2
32	Dolnath Gautam	56	1	Kavrepalanchowk	2	1	2
33	Nawaraj Gautam	46	1	Kavrepalanchowk	5	1	2
34	Gopini Gautam	60	0	Kavrepalanchowk	0	1	1
35	Apashra Gautam	47	0	Kavrepalanchowk	0	1	1
36	BholaNath Gautam	66	1	Kavrepalanchowk	2	1	1
37	Aatma ram Gautam	40	1	Kavrepalanchowk	5	1	2
38	Bhimsen Gautam	44	1	Kavrepalanchowk	3	1	1
39	Laxmi Sapkota	30	0	Kavrepalanchowk	0	1	2
40	Krishna Lamsal	56	1	Kavrepalanchowk	1	1	1
41	Vishnu Pd. Sapkota	40	1	Kavrepalanchowk	3	1	2
42	Ram Krishna Lamsal	37	1	Kavrepalanchowk	3	1	1
43	Taranath Lamsal	47	1	Kavrepalanchowk	1	1	1
44	Dinanath Lamsal	80	1	Kavrepalanchowk	1	1	2
45	Hari Saran lamsal	42	1	Kavrepalanchowk	3	1	1
46	Ghambhir Lamsal	55	1	Kavrepalanchowk	0	1	1
47	Ganesh Lamsal	45	1	Kavrepalanchowk	3	1	1
48	Sabitra Lamsal	35	0	Kavrepalanchowk	1	1	1
49	Shiva Lamsal	45	1	Kavrepalanchowk	3	1	3
50	Ram Chandra Sapkota	47	1	Kavrepalanchowk	3	1	3
51	Sambhu Pd. Phuyal	37	1	Kavrepalanchowk	4	1	1
52	Ram Hari Phuyal	75	1	Kavrepalanchowk	0	1	2
53	Bir Bd. Shrestha	80	1	Kavrepalanchowk	0	1	1
54	Kulbahadur Shrestha	47	1	Kavrepalanchowk	3	1	1
55	Dhan Bahadur Shrestha	80	1	Kavrepalanchowk	0	1	1
56	Ram Lal Shrestha	63	1	Kavrepalanchowk	2	1	1
57	Kaji Bd. Shrestha	75	1	Kavrepalanchowk	0	1	1
58	Ram Bhakta Shrestha	38	1	Kavrepalanchowk	3	1	1
59	Narayan Pd. Lamsal	53	1	Kavrepalanchowk	3	1	1
60	Gopal Gautam	39	1	Kavrepalanchowk	3	1	1
61	Nagendra Ghimere	38	1	Panchthar	3	1	1
62	Ghanshyam Ghimere	43	1	Panchthar		1	2
63	Kul Pd. Nemang	49	1	Panchthar	2	4	2
64	Kebal Phuyal	47	1	Panchthar	3	1	2
65	Deg Pd. Bhattrai	49	1	Panchthar		1	2
66	Bhim Pd. Phuyal	25	1	Panchthar	5	0	1
67	Pushpa lal Phuyal	74	1	Panchthar	1	1	1
68	Punya khatiwada	28	1	Panchthar		1	2
69	Dadi Ram Baskota	62	1	Panchthar	1	1	1
70	Harkamati Nebarg	79	0	Panchthar	0	1	1
71	Durbar Bd. Nemarg	69	1	Panchthar	1	1	1
72	Bhupendra Pariyar	47	1	Panchthar	2	1	1
73	Ded Bd. Pariyar	61	1	Panchthar	1	1	2
74	Dev Pd. Shrestha	26	1	Panchthar	2	1	1
75	Ramesh Pd. Dahal	42	1	Panchthar	2	1	2

S.No	Name	Age	Gender	Address	EL (outliers)	Marital Status	Economic Activitie
76	Bir Bd. Nemarg	42	1	Panchthar	2	1	2
77	Mani Pd. Nemarg	84	1	Panchthar	1	1	2
78	Dil Kumari Sambamphe	43	0	Panchthar	1	1	2
79	Rupdhoj Nemarg	45	1	Panchthar	3	1	1
80	Meghendra Angdembe	40	1	Panchthar	3	1	2
81	Mani Kr. Nemarg	37	1	Panchthar	1	0	1
82	Padma Raj Nemang	43	1	Panchthar	3	1	1
83	Surya Timilsina	35	1	Panchthar	4	1	1
84	Subarna Chemjong	58	1	Panchthar	3	1	2
85	Babita Nemang	50	1	Panchthar	4	1	2
86	Hem Pd. Acharya	58	1	Panchthar	1	1	1
87	Dak pd. Phuyal	42	1	Panchthar	3	1	1
88	Dhan maya Nemang	50	1	Panchthar	1	4	1
89	Narayan Bastola	40	1	Panchthar	1	1	1
90	Milan Ghimere	22	1	Panchthar	5	0	1

HH Members (out	HH Income	TV-No	TV-TW	TV-THr	TV-TEC(W	LED-No.	LED-TW	LED-THr	LED-TEC	CFL-No.
5	1	0	0	0	0	0	0	0	0	0
4	2	1	80	3	240	5	5	2	50	0
4	2	1	80	3	240	1	5	3	15	0
3	2	1	80	4	320	0	0	0	0	3
5	2	0	0	0	0	1	5	2	10	2
4	2	0	0	0	0	3	10	2	60	0
2	1	0	0	0	0	0	0	0	0	0
6	1	0	0	0	0	0	0	0	0	0
5	2	1	80	2	160	2	5	3	30	0
6	2	0	0	0	0	1	5	3	15	0
4	2	0	0	0	0	0	0	0	0	0
	2	1	80	6	480	6	5	3	90	0
7	2	0	0	0	0	4	5	3	60	0
4	1	0	0	0	0	0	0	0	0	0
3	2	0	0	0	0	0	0	0	0	1
5	2	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0
	2	1	80	0	0	0	0	0	0	3
5	2	0	0	0	0	0	0	0	0	1
5	2	2	116	2	464	5	2	5	50	0
8	2	0	0	0	0	5	5	2	50	0
5	2	1	80	3	240	3	5	2	30	0
4	1	1	80	0	0	5	5	2	50	0
7	2	1	80	3	240	8	5	2	80	1
3	1	0	0	0	0	2	5	3	30	0
3	2	1	100	1	100	4	5	2	40	0
8	2	2	180	5	1800	8	5	2	80	0
4	1	0	0	0	0	3	5	2	30	0
4	2	1	100	2	200	5	5	2	50	0
4	2	0	0	0	0	5	5	2	50	0

HH Members (out	HH Income	TV-No	TV-TW	TV-THr	TV-TEC(W	LED-No.	LED-TW	LED-THr	LED-TEC	CFL-No.
2	2	0	0	0	0	4	5	4	80	1
2	2	1	80	6	480	4	5	3	60	0
2	2	1	80	3	240	0	0	0	0	1
	2	1	80	4	320	0	0	0	0	0
1	2	0	0	0	0	0	0	0	0	0
4	2	1	80	5	400	0	0	0	0	1
4	2	1	100	6	600	15	5	5	375	3
1	1	1	80	0	0	0	0	0	0	1
3	2	1	68	1	68	0	0	0	0	6
4	2	1	80	4	320	0	0	0	0	5
4	2	1	90	5	450	19	5	5	475	0
3	2	1	90	2	180	0	0	0	0	5
6	2	1	80	3	240	17	5	3	255	1
4	2	1	80	2	160	0	0	0	0	0
4	2	1	100	6	600	0	0	0	0	2
5	2	1	100	4	400	0	0	0	0	2
3	2	1	100	3	300	0	0	0	0	4
4	1	1	100	2	200	0	0	0	0	2
1	2	1	80	2	160	15	5	3	225	0
1	2	1	100	2	200	0	0	0	0	0
4	2	0	0	0	0	0	0	0	0	0
4	2	1	100	3	300	0	0	0	0	0
4	2	1	80	1	80	0	0	0	0	0
5	2	0	0	0	0	0	0	0	0	4
1	1	0	0	0	0	2	10	3	60	0
1	1	0	0	0	0	2	5	4	40	2
3	2	0	0	0	0	1	3	5	15	0
4	2	1	80	2	160	0	0	0	0	2
5	2	1	80	3	240	11	5	4	220	0
5	2	0	0	0	0	0	0	0	0	2
5	2	1	60	5	300	7	5	4	140	3
3	2	1	80	3	240	8	5	4	160	2
	2	1	120	5	600	8	5	4	160	0
4	2	0	0	0	0	8	5	4	160	0
3	2	0	0	0	0	0	0	0	0	7
7	2	1	80	4	320	10	5	5	250	0
4	2	1	80	4	320	4	5	4	80	3
4	2	1	36	5	180	8	5	5	200	0
4	2	1	100	5	500	7	5	4	140	0
3	2	1	120	5	600	8	5	4	160	0
3	2	1	100	4	400	7	5	4	140	0
7	2	1	80	3	240	3	3	5	45	2
4	2	0	0	0	0	4	3	5	60	0
4	1	1	125	4	500	5	5	5	125	1
4	2	1	100	4	400	4	3	5	60	0

HH Members (out	HH Income	TV-No	TV-TW	TV-THr	TV-TEC(W	LED-No.	LED-TW	LED-THr	LED-TEC	CFL-No.
7	2	1	80	4	320	5	5	5	125	0
4	2	1	80	4	320	10	5	5	250	2
3	2	1	100	4	400	21	3	4	252	0
5	2	1	80	5	400	10	5	4	200	0
2	2	1	80	4	320	16	3	4	192	1
1	1	0	0	0	0	3	3	4	36	0
5	2	1	90	4	360	9	3	4	108	3
5	2	1	125	4	500	15	3	4	180	0
3	2	1	80	5	400	15	5	4	300	0
3	2	1	125	5	625	10	3	4	120	0
4	2	0	0	0	0	6	5	4	120	2
4	2	1	80	4	320	10	3	4	120	0
	1	0	0	0	0	3	5	4	60	0
4	1	0	0	0	0	6	5	4	120	2
1	2	1	80	4	320	4	5	3	60	2

CFL-TW	CFL-THr	CFL-TEC	Inca-No.	Inca-TW	Inca-THr	Inca-TEC	SP-No.	RP-No.	0t-No.	Ot-Whr
0	0	0	0	0	0	0	1	2	0	0
0	0	0	2	100	2	400	3	2	0	0
0	0	0	2	100	3	600	0	2	0	0
15	3	135	1	100	3	300	0	0	0	0
15	2	60	1	100	3	300	0	2	0	0
0	0	0	0	0	0	0	0	2	0	0
0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	2	0	0
0	0	0	2	100	3	600	1	1	0	0
0	0	0	2	60	3	360	0	2	0	0
0	0	0	1	40	3	120	0	3	0	0
0	0	0	0	0	0	0	1	3	0	0
0	0	0	5	60	3	900	0	2	0	0
15	2	30	5	60	2	600	0	3	0	0
0	0	0	5	60	3	900	0	3	0	0
0	0	0	7	80	3	1680	0	3	0	0
15	3	135	1	100	3	300	2	2	0	0
15	2	30	1	60	2	120	0	2	0	0
0	0	0	0	0	0	0	3	1	1	50
0	0	0	0	0	0	0	0	2	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	1	0	0
15	2	30	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	1	0	1	1500
0	0	0	0	0	0	0	4	2	1	1450
0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	1	2	0	0
0	0	0	0	0	0	0	0	3	0	0

CFL-TW	CFL-THr	CFL-TEC	Inca-No.	Inca-TW	Inca-THr	Inca-TEC	SP-No.	RP-No.	0t-No.	Ot-Whr
20	4	80	3	60	4	720	2	1	1	110
0	0	0	0	0	0	0	0	1	1	40
15	4	60	1	60	1	60	1	2	1	80
0	0	0	2	60	3	360	0	1	0	0
0	0	0	2	60	3	360	0	1	1	40
15	4	60	4	60	4	960	2	2	1	1910
15	3	135	0	0	0	0	3	0	1	890
11	3	33	1	60	3	180	1	1	1	850
15	4	360	0	0	0	0	0	0	0	0
20	4	400	0	0	0	0	3	2	1	850
0	0	0	0	0	0	0	1	1	0	0
10	3	150	0	0	0	0	1	0	0	0
15	1	15	1	60	2	120	2	1	1	60
0	0	0	5	60	3	900	0	2	1	800
15	3	90	2	60	4	480	0	2	1	800
10	4	80	2	60	2	240	1	2	2	40
15	3	180	0	0	0	0	2	1	1	800
11	3	66	2	60	3	360	1	1	1	850
0	0	0	0	0	0	0	0	1	2	40
0	0	0	1	60	3	180	1	0	1	40
0	0	0	3	60	3	540	3	1	0	0
0	0	0	3	60	2	360	1	1	0	0
0	0	0	5	60	3	900	1	2	1	40
15	3	180	0	0	0	0	4	1	1	40
0	0	0	0	0	0	0	0	0	0	0
10	4	80	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0	0
15	4	120	0	0	0	0	4	0	0	0
0	0	0	0	0	0	0	0	2	1	60
15	4	120	3	60	4	720	2	1	0	0
11	4	132	0	0	0	0	2	0	0	0
9	4	72	0	0	0	0	2	1	0	0
0	0	0	0	0	0	0	1	1	0	0
0	0	0	0	0	0	0	1	4	1	35
9	3	189	0	0	0	0	1	2	1	35
0	0	0	0	0	0	0	0	5	0	0
9	4	108	1	60	4	240	1	2	0	0
0	0	0	0	0	0	0	3	1	0	0
0	0	0	0	0	0	0	3	4	0	0
0	0	0	0	0	0	0	0	2	0	0
0	0	0	0	0	0	0	1	2	0	0
15	5	150	0	0	0	0	0	2	0	0
0	0	0	0	0	0	0	1	2	0	0
15	5	75	0	0	0	0	3	0	0	0
0	0	0	0	0	0	0	0	3	0	0

CFL-TW	CFL-THr	CFL-TEC	Inca-No.	Inca-TW	Inca-THr	Inca-TEC	SP-No.	RP-No.	0t-No.	Ot-Whr
0	0	0	0	0	0	0	2	2	0	0
15	5	150	0	0	0	0	3	2	0	0
0	0	0	0	0	0	0	2	2	1	50
0	0	0	0	0	0	0	0	3	0	0
20	4	80	0	0	0	0	2	0	0	0
0	0	0	0	0	0	0	0	0	0	0
15	3	135	0	0	0	0	3	0	0	0
0	0	0	0	0	0	0	3	2	0	0
0	0	0	0	0	0	0	4	0	1	50
0	0	0	0	0	0	0	2	1	0	0
15	4	120	0	0	0	0	1	4	0	0
0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0	0
15	4	120	0	0	0	0	0	2	0	0
15	3	90	0	0	0	0	1	1	0	0

Ot-Hr	Ot-TEC	Total Elecrticity Consumption	TEC in Kwhr	TEC in Month KWhr(outlie	TEC in Month
0	0	0	0	0	0
0	0	690	0.69	20.7	20.7
0	0	855	0.855	25.65	25.65
0	0	755	0.755	22.65	22.65
0	0	370	0.37	11.1	11.1
0	0	60	0.06	1.8	1.8
0	0	0	0	0	0
0	0	0	0	0	0
0	0	190	0.19	5.7	5.7
0	0	615	0.615	18.45	18.45
0	0	360	0.36	10.8	10.8
0	0	690	0.69	20.7	20.7
0	0	60	0.06	1.8	1.8
0	0	900	0.9	27	27
0	0	630	0.63	18.9	18.9
0	0	900	0.9	27	27
0	0	1680	1.68		50.4
0	0	435	0.435	13.05	13.05
0	0	150	0.15	4.5	4.5
2	100	514	0.514	15.42	15.42
0	0	50	0.05	1.5	1.5
0	0	270	0.27	8.1	8.1
0	0	50	0.05	1.5	1.5
0	0	350	0.35	10.5	10.5
0	0	30	0.03	0.9	0.9
0.16	240	140	0.14	4.2	4.2
0.58	841	1880	1.88		56.4
0	0	30	0.03	0.9	0.9
0	0	250	0.25	7.5	7.5
0	0	50	0.05	1.5	1.5

Ot-Hr	Ot-TEC	Total Elecrticity Consumption	TEC in Kwhr	TEC in Month KWhr(outlie	TEC in Month
6	660	880	0.88		26.4
4	160	540	0.54	16.2	16.2
2	160	360	0.36	10.8	10.8
0	0	680	0.68	20.4	20.4
1	40	360	0.36	10.8	10.8
4	7640	1420	1.42		42.6
4	3560	1110	1.11		33.3
0.66	561	213	0.213	6.39	6.39
0	0	428	0.428	12.84	12.84
0.66	561	720	0.72	21.6	21.6
0	0	925	0.925	27.75	27.75
0	0	330	0.33	9.9	9.9
3	180	630	0.63	18.9	18.9
0.66	528	1060	1.06	31.8	31.8
1	800	1170	1.17	35.1	35.1
3	240	720	0.72	21.6	21.6
1	800	480	0.48	14.4	14.4
1	850	626	0.626	18.78	18.78
3	240	385	0.385	11.55	11.55
2	80	380	0.38	11.4	11.4
0	0	540	0.54	16.2	16.2
0	0	660	0.66	19.8	19.8
3	120	980	0.98	29.4	29.4
2	80	180	0.18	5.4	5.4
0	0	60	0.06	1.8	1.8
0	0	120	0.12	3.6	3.6
0	0	15	0.015	0.45	0.45
0	0	280	0.28	8.4	8.4
3	180	460	0.46	13.8	13.8
0	0	840	0.84	25.2	25.2
0	0	572	0.572	17.16	17.16
0	0	472	0.472	14.16	14.16
0	0	760	0.76	22.8	22.8
3	105	160	0.16	4.8	4.8
3	105	189	0.189	5.67	5.67
0	0	570	0.57	17.1	17.1
0	0	748	0.748	22.44	22.44
0	0	380	0.38	11.4	11.4
0	0	640	0.64	19.2	19.2
0	0	760	0.76	22.8	22.8
0	0	540	0.54	16.2	16.2
0	0	435	0.435	13.05	13.05
0	0	60	0.06	1.8	1.8
0	0	700	0.7	21	21
0	0	460	0.46	13.8	13.8

Ot-Hr	Ot-TEC	Total Elecrticity Consumption	TEC in Kwhr	TEC in Month KWhr(outlie	TEC in Month
0	0	445	0.445	13.35	13.35
0	0	720	0.72	21.6	21.6
3	150	652	0.652	19.56	19.56
0	0	600	0.6	18	18
0	0	592	0.592	17.76	17.76
0	0	36	0.036	1.08	1.08
0	0	603	0.603	18.09	18.09
0	0	680	0.68	20.4	20.4
4	200	700	0.7	21	21
0	0	745	0.745	22.35	22.35
0	0	240	0.24	7.2	7.2
0	0	440	0.44	13.2	13.2
0	0	60	0.06	1.8	1.8
0	0	240	0.24	7.2	7.2
0	0	470	0.47	14.1	14.1

Stablizer	Monthly E	Fuel wooc	LPG	EPS-Own	Electrical Appliance Want in Future
0	0	200	0	0	Lights, mobile charging,TV
1	390	240	1	0	Induction cooker, Rice Cooker
1	100	260	0	0	Rice cooker, more lights
1	80	200	0	0	0
0	80	200	0	0	Rice cooker, TV, Motor
0	80	200	0	0	Rice cooker, TV
0	80	200	0	0	Rice cooker, TV
0	0	200	0	0	TV, Light
1	80	200	0	1	Iron, Tailoring machine. Rice cooker
0	80	280	0	0	Rice cooker. TV.More Light
0	80	160	0	0	Rice cooker.TV, heater
1	80	240	0	1	Ricecooker
0	80	200	0	0	Rice Cooker, TV, Heater
0	80	200	0	0	Rice Cooker, TV
0	80	160	0	1	TV, Computer, Rice cooker, induction cooker
0	80	200	0	1	Ricecooker,TV
0	80	200	0	0	TV, Ricecooker
1	80	280	0	0	Rice cooker
0	80	160	0	0	Rice cooker, TV, more Light
1	80	160	1	1	induction cooker, Rice Cooker
0	80	200	0	0	Rice cooker, TV
0	80	200	0	0	Induction cooker, Rice Cooker
0	80	240	0	0	Rice cooker
1	80	280	0	0	Induction cooker, Rice Cooker
0	80	200	0	0	Rice cooker, TV, more Light
1	80	160	1	1	Rice cooker
1	80	0	1	1	Induction cooker
0	80	240	0	0	Rice cooker, TV, more Lights
1	80	280	0	1	Induction cooker, Rice Cooker
0	80	280	0	0	Induction cooker, Rice Cooker

Stablizer	Monthly E	Fuel wooc	LPG	EPS-Own	Electrical Appliance Want in Future
0	150	120	1	1	Induction, rice cooker, Motor
0	80	240	1	0	Induction, rice cooker, Motor
0	80	160	1	0	
0	80	80	1	0	Rice cooker, Fridge
0	80	200	1	0	Rice cooker, Fridge, TV
0	80	800	1	1	Motor
0	800	320	1	1	Induction
0	80	160	1	0	Induction, Fridge, Motor,
0	80	160	1	0	Induction, Rice cooker, Fridge
0	80	120	1	0	Induction, Fridge
0	80	160	1	0	Induction, Rice cooker
0	80	200	1	0	Induction, Rice Cooker, Motor
0	100	280	1	0	Induction, Rice Cooker, Motor
0	80	280	0	0	Induction Cooker
0	80	280	0	0	Induction Cooker, Fridge
0	80	280	0	0	Induction cooker
0	80	320	0	0	Induction Cooker
0	80	400	0	0	Induction, LPG
0	500	280	1	0	Induction, Rice cooker
0	80	80	1	0	Induction, Rice cooker
0	80	160	1	0	Induction, Rice cooker and TV
0	80	160	0	0	Induction, Rice cooker
0	80	200	1	0	Induction, Rice cooker, Fridge
0	80	320	0	0	Induction, Rice cooker, LPG
0	80	120	0	0	Induction, Rice cooker, LPG, Fridge
0	80	320	0	0	induction, Rice cooker, TV
0	80	280	0	0	induction, Rice cooker
0	80	280	1	0	induction, Rice cooker, Fridge
0	80	120	1	0	induction, Rice cooker
0	80	280	0	0	induction, Rice cooker, LPG, TV
0	80	400	0	0	Rice cooker, iron, fridge
0	160	240	1	0	Rice cooker, iron, fridge, induction
0	80	240	0	0	Rice cooker, iron, fridge
0	80	400	0	0	Rice cooker, others
0	80	240	0	0	Induction, Rice cooker, TV, Fridge
0	160	600	0	0	Induction, Rice cooker, Iron
0	80	400	0	0	Rice cooker, Fridge
0	80	600	0	0	Rice cooker, Fridge, induction cooker
0	80	800	0	0	Rice cooker, Iron
0	80	1200	0	0	Induction, Rice cooker
0	80	240	0	0	Induction, Rice cooker
0	80	600	1	0	Induction, Rice cooker, Fridge
0	80	600	0	0	Rice cooker, TV
1	80	600	0	0	Rice cooker, Induction
0	80	400	0	0	Rice cooker

Stablizer	Monthly E	Fuel wood	LPG	EPS-Own	Electrical Appliance Want in Future
0	80	600	0	0	Rice Cooker
0	80	800	1	0	Rice Cooker, Induction and Fridge
0	160	400	1	0	Rice Cooker, Induction and Fridge
0	80	400	0	0	Rice Cooker, Induction and Fridge
0	80	160	1	0	Rice Cooker, Induction
0	40	280	0	0	Rice Cooker, Induction, TV
0	80	400	1	0	Rice Cooker, Induction, Fridge
0	80	600	0	0	Rice Cooker, Induction
0	80	600	1	0	Rice Cooker, Induction, Fridge
0	80	400	1	0	Rice Cooker, Induction, Fridge
0	80	400	0	0	Rice Cooker, Induction
0	80	400	0	0	Rice Cooker, Induction
0	40	280	0	0	Rice Cooker, Induction, TV
0	80	400	0	0	Rice Cooker, Induction, TV
0	80	400	0	0	Rice Cooker, Induction

A.2 India

NOTE: This is a master sheet. Do not make any changes. Please copy data to make changes or analyse the data.

Sl.No.	Questionaire Number	State	District	Administration	Village	Village type	Survey Status	No. of Family	No. of HH Member	Male	Female	Age Group						
												0-14	14-25	25-50	50+	HH Income/Month	Major Income source 1	Major income source 2
1	JA01	Arunachal	Lower Dib	Hunli	Jamupani	NE	1-Complete	1	1	1	0	0	0	1	0	5000	10	
2	JA02	Arunachal	Lower Dib	Hunli	Jamupani	NE	4	1	4	1	3	1	1	2		480	16	1
3	JA03	Arunachal	Lower Dib	Hunli	Jamupani	NE	1	1	5	0	5	1	2	1	1		1	15
4	JA04	Arunachal	Lower Dib	Hunli	Jamupani	NE	4	1	1	0	1				1	900	5	
5	JA05	Arunachal	Lower Dib	Hunli	Jamupani	NE	1	1	8	3	5	5	1	2	0		15	1
6	JA06	Arunachal	Lower Dib	Hunli	Jamupani		1	1	3	1	2		2		1	1000	8	1
7	JA07(School)	-------------------Not Sure if I have to add this here-----------------																
8	NC01	Arunachal	Lower Dib	Hunli	New Chetani	NE	1	1	5	2	3	3		2		4000	1	5
9	NC02	Arunachal	Lower Dib	Hunli	New Chetani	NE	1	1	10	3	7	4	4	2	0	14700	1	5
10	NC03	Arunachal	Lower Dib	Hunli	New Chetani	NE	4	1	6	3	3	2	1	3	1	8000	16	4
11	HA01	Arunachal	Anjaw	Hawai	Hayum	NE	1	1	6	4	2	0	3	1	1	21500	16	1
12	HA02	Arunachal	Anjaw	Hawai	Hayum	NE	1	1	4	2	2	1	1	1	1	13300	1	11
13	HA03	Arunachal	Anjaw	Hawai	Hayum	NE	1	2	6	3	3	3	2	1	0	3000	1	
14	HA04	Arunachal	Anjaw	Hawai	Hayum	NE	1	2	2	1	1	0	0	2	0	3000	1	
15	HA05	Arunachal	Anjaw	Hawai	Hayum	NE	1	1	8	3	5	2	1	3	2	25000	1	16
16	HA06	Arunachal	Anjaw	Hawai	Hayum	NE	4	1	4	2	2	1	0	2	1	34000	10	1
17	HA07	Arunachal	Anjaw	Hawai	Hayum	NE	1	2	7	3	4	1	4	0	2	7000	16	1
18	HA08	Arunachal	Anjaw	Hawai	Hayum	NE	1	1	6	4	2	3	0	2	0	4500	1	
19	HA09	Arunachal	Anjaw	Hawai	Hayum	NE	1	1	4	1	3	2	0	2	0	1000	5	1
20	HA10	Arunachal	Anjaw	Hawai	Hayum	NE	1	2	7	3	4	4	1	2	0	5000	1	
21	HA11	Arunachal	Anjaw	Hawai	Hayum	NE	1	3	11	6	5	3	5	2	0	11000	5	1
22	HA12	Arunachal	Anjaw	Hawai	Hayum	NE	1	3	8	3	5	5	0	2	1	20000	1	16
23	HM01	Arunachal	Anjaw	Hawai	Hamatong	NE	1	2	4	3	1	2	0	2		35000	16	1
24	HM02	Arunachal	Anjaw	Hawai	Hamatong	NE	1	1	5	3	22	2	1	2	0	6500	16	1
25	HM03	Arunachal	Anjaw	Hawai	Hamatong	NE	1	1	8	3	5	3	2	1	1	3000	1	4
26	HM04	Arunachal	Anjaw	Hawai	Hamatong	NE	1	1	6	2	4	3	0	2	1	9000	6	1
27	HM05	Arunachal	Anjaw	Hawai	Hamatong	NE	1	1	4	3	1	2		2		3000	1	
28	HM06	Arunachal	Anjaw	Hawai	Hamatong	NE	1	1	2	1	1				2	4500	6	1
29	PI01	Arunachal	Anjaw	Hawai	Pitong	NE	1	4	8	4	4	5		2	1	48000	1	15
30	PI02	Arunachal	Anjaw	Hawai	Pitong	NE	1	2	7	2	5	3	2	2		8000	1	
31	PI03	Arunachal	Anjaw	Hawai	Pitong	NE	1	2	7	6	1	3	2	2	0	12000	1	
32	PI04	Arunachal	Anjaw	Hawai	Pitong	NE	4	1	6	5	1	4		2			1	4
33	KH01	Arunachal	Anjaw	Hawai	Khetong	NE	1	1	5	3	2	2	2	1		9000	1	6
34	SI01	Arunachal	Anjaw	Hawai	Siet	NE	4	2	5	2	3	2		2	1	8000	1	6
35	SI02	Arunachal	Anjaw	Hawai	Siet	NE	4	2	8	4	4	5		2	1	35000	16	1
36	MG01	Arunachal	Anjaw	Hawai	Mangom	NE	1	1	8	4	4	5		2	1	3500	1	
37	MG02	Arunachal	Anjaw	Hawai	Mangom	NE	1	2	7	5	2	1	3	3	0	5000	1	
38	MG03	Arunachal	Anjaw	Hawai	Mangom	NE	1	1	6	4	2	3	1	2		6000	1	
39	MG04	Arunachal	Anjaw	Hawai	Mangom	NE	1	2	6	2	4	4		2		11000	1	6
40	MG05	Arunachal	Anjaw	Hawai	Mangom	NE	4	2	5	2	3	2		2	1	12000	1	16
41	MG06	Arunachal	Anjaw	Hawai	Mangom	NE	1	1	6	3	3		1	3	2	5000	1	9
42	MG07	Arunachal	Anjaw	Hawai	Mangom	NE	1	4	4	2	2	2		2		3000	1	5
43	MG08	Arunachal	Anjaw	Hawai	Mangom	NE	1	1	5	4	1	2	1	1		27000	15	1,4
44	NE01	Arunachal	Lower Dib	Hunli	New Elope	E	1	1	7	4	3		5		2	60000	1	
45	KE01	Arunachal	Lower Dib	Roing	Kevalli	E	4	1	9	5	4	2	3	3	1		1	15, Remit
46	KE02	Arunachal	Lower Dib	Roing	Kevalli	E	1	1	6	4	2	1	2	3		20000	7	16, 13, 1
47	GG01	UP	Sitapur	Biswan	Ganganagar	M	4	1	7	3	4	2	3	2		5000	13	
48	GG02	UP	Sitapur	Biswan	Ganganagar	M	1	1	6	3	3	3	1	2		12500	13	1,5
49	GG03	UP	Sitapur	Biswan	Ganganagar	M	1	1	8	4	4	1	3	2	2	20000	1	
50	GG04	UP	Sitapur	Biswan	Ganganagar	M	1	1	11	7	4	5	3	2	1	2300	1	6
51	GG05	UP	Sitapur	Biswan	Ganganagar	M	1	1	2	1	1			2		5000	15	15
52	RM01	UP	Sitapur	Biswan	Ramabhari	M	1	1	5	2	3	3		2		4500	5	
53	RM02	UP	Sitapur	Biswan	Ramabhari	M	1	1	5	4	1		3	2		12500	10	5,1
54	RM03	UP	Sitapur	Biswan	Ramabhari	M	1	1	5	4	1	3		2		4500	5	
55	RM04	UP	Sitapur	Biswan	Ramabhari	M	1	1	6	2	4	2	1		3	6000	5	1
56	RM05	UP	Sitapur	Biswan	Ramabhari	M	1	1	7	5	2	4	1	2		5000	5	
57	RM06	UP	Sitapur	Biswan	Ramabhari	M	1	1	8	4	4	5	1	2		7000	5	
58	RM07	UP	Sitapur	Biswan	Ramabhari	M	4	1	5	3	2	1	1	2	1	10000	5	
59	PK01	UP	Sitapur	Mahouli	Pakkarhpur	PE	1	1	4	3	1	2		2		25000	1	15
60	PK02	UP	Sitapur	Mahouli	Pakkarhpur	PE	1	1	3	2	1	1	1	1		6000	1	
61	PK03	UP	Sitapur	Mahouli	Pakkarhpur	PE	1	1	3	2	1		2		1	12500	6	1
62	PK04	UP	Sitapur	Mahouli	Pakkarhpur	PE	4	1	7	5	2	1	4	2			1	
63	PK05	UP	Sitapur	Mahouli	Pakkarhpur	PE	1	1	7	6	1	3	3	1		12500	1	
64	PK06	UP	Sitapur	Mahouli	Pakkarhpur	PE	1	1	6	4	2	2	2	1	1	20000	1	
65	MS01	UP	Sitapur	Mahouli	Mussafarpur	PE	4	1	18							21000	1	10
66	MS02	UP	Sitapur	Mahouli	Mussafarpur	NE	1	1	6	3	3	1	3	2		8000	6	
67	MS03	UP	Sitapur	Mahouli	Mussafarpur	NE	1	1	4	2	2	2		2		5000	1	5
68	MS04	UP	Sitapur	Mahouli	Mussafarpur	NE	1	1	5	3	2	1	3	1		17000	6	1
69	DG01	UP	Sitapur	Mahouli	Digrah	NE	3											
70	DG02	UP	Sitapur	Mahouli	Digrah	PE	1	1	8	5	3	1	4	2	1		1	
71	DG03	UP	Sitapur	Mahouli	Digrah	NE	1	1	4	4				3	1	8000	5	

NOTE: This i

Sl.No.	Questionaire Number	HH Income	Expenses													Total Monthly Expenses
		Remarks	Food	Housing	Health, medicine	Education	Lighting	Energy	Furniture	Transport	Communication, Mobile phone	Others1		Others 2		
												Name	Expenses	Name	Expenses	
1	JA01	Education/School Caretaker	500	0	100	0	230	450	0	800	100	Setupbox	375			2555
2	JA02	ASM's wife	3500	0	5000	10000	200	850	0	5000	700	Setupbox	370			25620
3	JA03	Yam hunting and farming	1000	0	0	2000	110	0	0	500	400	Setupbox	280			4290
4	JA04	Laborour					30									
5	JA05	Yam and Agriculture	3100	0	5000	1000	180	0	0	500	400	Setupbox	390			10570
6	JA06	Shop, Yam and cardamom	2000	0	500	1500	80	0	0	800	200					5080
7	JA07(School)															
8	NC01	Head labor, cardamom	2000	0	600	0	190	350	0	800	200	Setupbox	290	Guests	1000	5430
9	NC02	Head labor, cardamom	4000	0	8000	8500	170	300	0	3000	300	Setupbox	350			24620
10	NC03	Govt. Employee, Yam	2000	0	3000	2500	320	0	0	2000	900	Setupbox	375			11095
11	HA01	Block-Coordinator, farming, yam	1500	0	3000	8500	90	0	0	2000	500					15590
12	HA02	Midwife, priest and farming(cardamom and opium)	5000	0	4000	5000	180	0	0	3500	0					17680
13	HA03	Opium and cardamom	2000	0	1000	4000	75	0	0	1500	0					8575
14	HA04	Opium and cardamom	2000	0	1500	0	150	0	0	1000	100					4750
15	HA05	Farming, Gram panchayat member	4000	0	5000	12000	180	1200	0	1500	200					24080
16	HA06	Teacher, Farming	4000	0	5000	0	200	1200	0	1500	200					12100
17	HA07	Hydropower labor & Cardamom, opium farming	3000	0	3000	4000	200	0	0	2000	450					12650
18	HA08	Cardamom	8000	0	2500	0	60	0	0	1000	100					11660
19	HA09	Hydropower labor & Cardamom, opium farming	6000	0	3000	0	120	0		1500	150					10770
20	HA10	Opium and cardamom	3000	0	500	5000	300	0	0	1000	150					9950
21	HA11	Hydropower labor & Cardamom, opium farming	4500	0	1000	1000	180	0	0	4000	400					11080
22	HA12	Hydropower employee and cardamon, opium	6000	0	2500	12500	270	0	0	4000	100					25370
23	HM01	Peon at school & farming	8000	0	1600	5000	60			2000	300					16960
24	HM02	Nursery caretaker, farming	6000		1500	5000	120	0	0	1000	100					13720
25	HM03	Cardamom, opium and Yam	7000	0	0	2000	300	0	0	3000	200					12500
26	HM04	Plumbing and farming	4000		3500		270			1000	100					8870
27	HM05	Farming	3000		1500	500	190			1000						6190
28	HM06	Weaving, Farming	2000		500		90			1500		Weaving	500			4590
29	PI01	Sumo operator & Farming	4000	0	1500	8000	260	0	0	1000	250	Setupbox	650	Fuel & dri	27500	43160
30	PI02	Cardamom & maize farming	3000	0	4000	6000	180	0	0	1500	150					14830
31	PI03	Cardamom & rice	7000		4000	10000	210	0	0	3000	150					24360
32	PI04	Yam, cardamom & opium					210			1000						1210
33	KH01	Driving and farming	2500	0	500	1000	360	0	0	500	3000					7860
34	SI01	Farming & carepentry	5000		3000	500	230	1200		3000	200					13130
35	SI02	Teacher + Farming	4500		3000	6000	130			3000						16630
36	MG01	Farming + yam	4000		3000	4000	90			1500						12590
37	MG02	Farming +Yam	3000		2500	4000	190			2000	150					11840
38	MG03	Farming +Yam	3000		1000	4000	120			1500	100					9720
39	MG04	Plumber+farm	3000		3000	1000	200			1000						8200
40	MG05	ASM + Farming	3000		5000	6000	60	1200		4000	500					19760
41	MG06	Farming + Banking	2000		2500	2000	120			2000	200					8820
42	MG07	Farming + Labor	2500	0	500					1000						4000
43	MG08	Sumo owner + Yam+ Farming	3000		1000	6500	180			10000	100	Setupbox	400			21180
44	NE01	Cardamom	5000	0	0	15000	180	300	0	2000	1000	Setupbox	300			23780
45	KE01	Agriculture, Broomstick	4000							500	400	Setupbox	375			5275
46	KE02	Tourism, farming, formal employment	4000	0	2000	0	180	450	0	7000	800	Setupbox	250			14680
																0
																0
47	GG01	Gas Agency					185	750		2000	100	Diesel pur	3000			6035
48	GG02	Farming, milk sale, labour	1500			1000	155	500			150					3305
49	GG03	Sugarcane & wheat	8000		2000	5000	150	750		900	100	Diesel pur	6000			22900
50	GG04	Sugarcane, wheat, paddy, electrician					200	375		800	130	Diesel pur	1500			3005
51	GG05	Milk selling, watchman	1500		4000		220									5720
52	RM01	Laborer	2500		1500		120				50					4170
53	RM02	Teaching, labourer, agriculture	4500		1500	3000	150	750		1000	200	Setupbox	100			11200
54	RM03	Laborer	2000		1000	70	170				50					3290
55	RM04	Laborer	4000		1200	600	120				50					5970
56	RM05	Laborer	4000		1500		180				100					5780
57	RM06	Laborer	2000		1000	70	170				100					3340
58	RM07	Laborer	6000		2500	100	170									8770
59	PK01	Agriculture and Tractor service	6000		500		150	500			500	Tractor fu	15000			22650
60	PK02	Agriculture	2500		1000		10	500		2000	150					6160
61	PK03	Driver, agriculture	3000		1500		150			1000	150					5800
62	PK04	Agriculture	5000		5000	20000	80				600					30680
63	PK05	Agriculture -sugarcane, wheat	2000			400	80			500	200	Agricultur	10000			13180
64	PK06	Agriculture	3000		1000	8000	100	700		3000						15800
65	MS01	Formal education and farming	10000		1500	10000	1200	750		2000	400					25850
66	MS02	Driver	4000		1000	1000	50			4000	100					10150
67	MS03	Laborer	4500		1000		100	300								5900
68	MS04	Driver, farmer	1500		8000		10				300					9810
69	DG01															0
70	DG02	Agriculture-sugarcane, peanuts, wheat	6000		1000	5000	50	300		1500	400	0				14250
71	DG03	Labourer	4000		1000		50									5050

NOTE: This is

Sl.No.	Questionaire Number	Energy Access														Total monthly expenses on energy	Light bulbs (incandesc			
		Electricity (National Grid)	Micro Grid	Solar Lantern (FC)	Kerosene Lamp	Candle	Flash Light/Battery based	Diesel or Petrol generator	Firewood	Stand-alone SHS (FC)	Service Fee or Repair	Others1		Others 2						
												Name	Expenses	Name	Expenses		W	No.	Hrs.	Total W
1	JA01			500			180		0	15000	50					15730				0
2	JA02			500			180		0	1500	20					2200				0
3	JA03						100		0	11500	10					11610				0
4	JA04						20				10					30				0
5	JA05						150		0	1500	30					1680				0
6	JA06						60		0	1500	20					1580				0
7	JA07(School)															0				0
8	NC01						150		0	11000	40					11190				0
9	NC02			500			150		0	0	20					670				0
10	NC03						300		0	5000	20					5320				0
11	HA01						80		0		10					90				0
12	HA02						180		0							180				0
13	HA03						60		0	3000	15					3075				0
14	HA04			1500			90		0	6000	60					7650				0
15	HA05			6000			180		0							6180				0
16	HA06			3000			200		0							3200	100	1	0	100
17	HA07			2400			160		0	3000	40					5600				0
18	HA08			7000			60		0							7060				0
19	HA09			1200			120									1320				0
20	HA10			3000			200		0	3000	100					6300				0
21	HA11			5000			180			3000						8180				0
22	HA12			3000			270	0	0	3000	0					6270	60	1	0	60
23	HM01						60	0	0	6000	10					6070				0
24	HM02			3000			120		0			Diesel	100			3220				0
25	HM03						300		0			Diesel	100			400				0
26	HM04						240			10000	30					10270				0
27	HM05						180		0	8000	10	Diesel lam	50			8240				0
28	HM06						60			5000	30					5090				0
29	PI01			2500					0	35000	60					37560				0
30	PI02			800			120		0	10000	60					10980				0
31	PI03			2000			180		0	3000	30					5210				0
32	PI04						180	0	0	6000	30					6210				0
33	KH01						300		0	8000	60					8360				0
34	SI01						200		0	5000	30					5230				0
35	SI02						100				30					130				0
36	MG01						90									90				0
37	MG02						90			100						190	100	1	0	100
38	MG03			3000			120									3120	100	1	0	100
39	MG04			2000	200		180	0	0		20					2400	20	1	0	20
40	MG05			2500			60	0								2560	100	1	0	100
41	MG06						120									120				0
42	MG07			2000								Diesel	50			2050				0
43	MG08			2400			150			10000	30					12580				0
44	NE01	180					180				20					380	60	2	2	120
45	KE01	120														120				0
46	KE02	120		7200			180				20					7520	5	8	6	40
																0				0
																0				0
47	GG01		120				65	3000								3185				0
48	GG02		120				35		0							155				0
49	GG03		120				20	6000		8000	10					14150				0
50	GG04		120		40		30	1500	0	8000	10					9700				0
51	GG05		120		70		30		0							220				0
52	RM01		120													120				0
53	RM02		120		110		30		0	5000	10					5270	100	1	0	100
54	RM03		120		50											170				0
55	RM04		120													120				0
56	RM05		120		50		10		0							180				0
57	RM06		120		50											170				0
58	RM07		120		50											170				0
59	PK01	Y				150										150				0
60	PK02	Y							0	4500	10					4510	100	2	5	200
61	PK03	100			50				0							150				0
62	PK04	Y			50		30		0							80	100	1	3	100
63	PK05	Y			50		30		0							80				0
64	PK06	Y					100			6500		Rechargeable light				6600	100	1	4	100
65	MS01	Y			150		30	1000		8000	20					9200				0
66	MS02	N		800	50											850				0
67	MS03	N		800	100											900				0
68	MS04	N								2350	10					2360				0
69	DG01															0				0
70	DG02	Y, 0														0				0
71	DG03				50											50				0

NOTE: This i

Sl.No.	Questionaire Number	ent)	Light bulbs (LED)					CFL Light					Lantern (Solar or any other)					Fan					Charger for mobile phone & Tablet							
		Total Wh	W	No.	Hrs.	Total W	Total Wh	W	No.	Hrs.	Total W	Total Wh	W	No.	Hrs.	Total W	Total Wh	W	No.	Hrs.	Total W	Total Wh	W	No.	Hrs.	Total W	Total Wh	W	No.	Hrs.
1	JA01	0	5	3	3	15	45				0	0		1	1	0	0	20	1	0	20	0	10.2	1	3	10.2	30.6	24	1	2
2	JA02	0	3	2	3	6	18				0	0				0	0				0	0				0	0			
3	JA03	0	3	2	3	6	18				0	0				0	0				0	0	2.7	1	2	2.7	5.4	27	1	3
4	JA04	0	3	1	3	3	9				0	0				0	0				0	0				0	0			
5	JA05	0	3	3	3	9	27				0	0				0	0				0	0	3.5	2	3	7	21	24	1	4
6	JA06	0	3	2	3	6	18				0	0				0	0				0	0	3	1	1	3	3			
7	JA07(School)	0				0	0				0	0				0	0				0	0				0	0			
8	NC01	0				0	0	15	4	3	60	180				0	0	20	1	4	20	80	6	1	2	6	12	24	1	8
9	NC02	0	3	3	3	9	27				0	0				0	0	20	1	2	20	40	10	1	2	10	20	120	1	3
10	NC03	0	3	4	4	12	48				0	0				0	0	20	1	2	20	40	5	3	2	15	30	25	1	3
11	HA01	0	3	1	6	3	18	9	3	0	27	0				0	0				0	0	2.3	3	2	6.9	13.8			
12	HA02	0	3	2	0	6	0				0	0				0	0				0	0				0	0			
13	HA03	0	3	1	6	3	18	15	1	0	15	0				0	0				0	0				0	0			
14	HA04	0	3	1	6	3	18	5	1	0	5	0	3	1	6	3	18				0	0	2.5	1	2	2.5	5			
15	HA05	0	3	2	0	6	0	21	2	0	42	0	7	1	6	7	42				0	0	3	2	2	6	12	30	1	0
16	HA06	0	7	2	0	14	0	9	1	0	9	0	15	2	6	30	180				0	0	2.5	2	2	5	10	30	1	0
17	HA07	0	5	1	6	5	30	15	3	0	45	0	5	1	6	5	30				0	0				0	0			
18	HA08	0				0	0	11	4	0	44	0	3	1	3	3	9				0	0	2.5	1	2	2.5	5			
19	HA09	0				0	0	11	1	0	11	0	3	2	6	6	36				0	0				0	0	50	1	0
20	HA10	0	6	1	3	6	18	14	1	0	14	0	3	1	6	3	18				0	0	2.5	1	1	2.5	2.5			
21	HA11	0				0	0				0	0	3	2	4	6	24				0	0	2.3	4	2	9.2	18.4	100	1	0
22	HA12	0	3	1	0	3	0	15	1	0	15	0	3	1	6	3	18				0	0	2.5	1	1	2.5	2.5	50	1	0
23	HM01	0	5	1	3	5	15	9	1	3	9	27				0	0				0	0	4.8	2	2	9.6	19.2			
24	HM02	0	9	1	0	9	0				0	0	3	1	6	3	18				0	0	4.8	1	2	4.8	9.6			
25	HM03	0				0	0	15	1	0	15	0				0	0				0	0				0	0			
26	HM04	0	5	1	3	5	15				0	0				0	0				0	0				0	0			
27	HM05	0	5	1	6	5	30				0	0				0	0				0	0				0	0			
28	HM06	0	7	1	3	7	21	15	1	0	15	0				0	0				0	0				0	0			
29	PI01	0	7	2	4	14	56				0	0				0	0				0	0	2.5	1	2	2.5	5	50	1	5
30	PI02	0	7	3	4	21	84				0	0	5	1	4	5	20				0	0	4.2	1	2	4.2	8.4			
31	PI03	0	7	1	4	7	28	15	2	0	30	0	3	1	6	3	18				0	0				0	0			
32	PI04	0	7	1	6	7	42				0	0				0	0				0	0				0	0	65	1	0
33	KH01	0	7	2	4	14	56				0	0				0	0				0	0	2.5	3	2	7.5	15			
34	SI01	0	5	1	4	5	20				0	0				0	0				0	0	2.4	1	2	2.4	4.8	32	1	0
35	SI02	0	5	2	5	10	50	15	1	0	15	0				0	0				0	0				0	0			
36	MG01	0	7	1	0	7	0				0	0				0	0				0	0				0	0			
37	MG02	0	5	2	4	10	40				0	0				0	0				0	0				0	0			
38	MG03	0	5	1	4	5	20	15	1	0	15	0	3	1	4	3	12				0	0	2.5	1	2	2.5	5	100	1	0
39	MG04	0	3	3	1	9	9				0	0	9	1	0	9	0				0	0				0	0			
40	MG05	0				0	0				0	0				0	0				0	0				0	0			
41	MG06	0	3	1	0	3	0	15	1	0	15	0	3	1	1	3	3				0	0	2.5	1	1	2.5	2.5	36	1	0
42	MG07	0				0	0	11	2	0	22	0	5	1	4	5	20				0	0				0	0			
43	MG08	0	7	1	6	7	42	15	2	0	30	0	5	1	3	5	15				0	0	2.5	1	2	2.5	5	36	1	3
44	NE01	240	3	2	2	6	12	11	1	3	11	33				0	0				0	0	5	2	2	10	20	30	1	7
45	KE01	0	5	9	3	45	135	20	2	8	40	320	5	1	1	5	5	40	3	3	120	360	2.5	3	2	7.5	15	24	1	6
46	KE02	240	5	1	1	5	5	15	1	6	15	90	5	1	1	5	5	40	4	2	160	320	5	1	2	5	10	30	1	6
		0				0	0				0	0				0	0				0	0				0	0			
		0				0	0				0	0				0	0				0	0				0	0			
47	GG01	0	1	2	7	2	14				0	0				0	0				0	0	2.5	1	2	2.5	5			
48	GG02	0	1	2	7	2	14				0	0				0	0				0	0	2.5	1	2	2.5	5			
49	GG03	0	1	3	7	3	21				0	0				0	0	3	2	6	6	36	3	3	2	9	18			
50	GG04	0	3	2	9	6	54				0	0				0	0	3	1	7	3	21	2.5	1	2	2.5	5			
51	GG05	0	1	2	7	2	14				0	0				0	0				0	0	2.5	1	2	2.5	5			
52	RM01	0	1	2	7	2	14				0	0				0	0				0	0	2.5	1	2	2.5	5			
53	RM02	0	1	2	7	2	14				0	0				0	0	3	1	5	3	15	2.5	3	2	7.5	15	30	1	5
54	RM03	0	1	2	7	2	14				0	0				0	0				0	0	2.5	2	2	5	10			
55	RM04	0	1	2	7	2	14				0	0				0	0				0	0	2.5	1	2	2.5	5			
56	RM05	0	1	2	7	2	14				0	0				0	0				0	0	2.5	1	2	2.5	5			
57	RM06	0	1	2	7	2	14				0	0				0	0				0	0	2.5	1	2	2.5	5			
58	RM07	0	1	2	7	2	14				0	0				0	0				0	0	2.5	1	2	2.5	5			
59	PK01	0	9	2	6	18	108				0	0				0	0	75	1	5	75	375	2.5	1	2	2.5	5	100	1	0
60	PK02	1000				0	0				0	0				0	0	24	1	7	24	168				0	0	120	1	0
61	PK03	0	5	1	3	5	15				0	0				0	0				0	0	2.5	1	2	2.5	5			
62	PK04	300	10	1	3	10	30				0	0				0	0	30	2	6	60	360	2.5	2	2	5	10			
63	PK05	0	7	1	6	7	42				0	0				0	0	75	2	6	150	900	2.5	2	2	5	10			
64	PK06	400	4	2	5	8	40				0	0				0	0	24	1	7	24	168	2.5	1	2	2.5	5			
65	MS01	0	5	3	4	15	60				0	0				0	0	75	2	3	150	450	2.5	4	2	10	20	30	1	0
66	MS02	0				0	0				0	0				0	0				0	0	2.5	2	2	5	10			
67	MS03	0				0	0				0	0				0	0				0	0	2.5	1	2	2.5	5			
68	MS04	0	1	2	2	2	4				0	0				0	0				0	0	2.5	3	2	7.5	15			
69	DG01	0				0	0				0	0				0	0				0	0				0	0			
70	DG02	0	4	2	3	8	24				0	0	5	1	2	5	10	80	2	3	160	480	2.5	3	2	7.5	15	100	1	5
71	DG03	0				0	0				0	0				0	0				0	0				0	0			

NOTE: This i

Sl.No.	Questionaire Number	Electrification Status																														
		TV		Video/CD/VCD/DVD					Radio					Computer/Laptop					Rice Cooker					Iron					Refrigerator			
		Total W	Total Wh	W	No.	Hrs.	Total W	Total Wh	W	No.	Hrs.	Total W	Total Wh	W	No.	Hrs.	Total W	Total Wh	W	No.	Hrs.	Total W	Total Wh	W	No.	Hrs.	Total W	Total Wh	W	No.	Hrs.	Total W
1	JA01	24	48				0	0				0	0				0	0				0	0				0	0				0
2	JA02	0	0				0	0				0	0				0	0				0	0				0	0				0
3	JA03	27	81				0	0				0	0				0	0				0	0				0	0				0
4	JA04	0	0				0	0				0	0				0	0				0	0				0	0				0
5	JA05	24	96				0	0				0	0				0	0				0	0				0	0				0
6	JA06	0	0				0	0				0	0				0	0				0	0				0	0				0
7	JA07(School)	0	0				0	0				0	0				0	0				0	0				0	0				0
8	NC01	24	192				0	0				0	0				0	0				0	0				0	0				0
9	NC02	120	360				0	0				0	0				0	0				0	0				0	0				0
10	NC03	25	75				0	0				0	0				0	0				0	0				0	0				0
11	HA01	0	0				0	0				0	0				0	0				0	0				0	0				0
12	HA02	0	0				0	0				0	0				0	0				0	0				0	0				0
13	HA03	0	0				0	0				0	0				0	0				0	0				0	0				0
14	HA04	0	0				0	0				0	0				0	0				0	0				0	0				0
15	HA05	30	0				0	0				0	0				0	0				0	0				0	0				0
16	HA06	30	0				0	0				0	0				0	0				0	0				0	0				0
17	HA07	0	0				0	0				0	0				0	0				0	0				0	0				0
18	HA08	0	0				0	0				0	0				0	0				0	0				0	0				0
19	HA09	50	0				0	0				0	0				0	0				0	0				0	0				0
20	HA10	0	0				0	0				0	0				0	0				0	0				0	0				0
21	HA11	100	0				0	0	60	1	4	60	240				0	0				0	0				0	0				0
22	HA12	50	0				0	0				0	0				0	0				0	0				0	0				0
23	HM01	0	0				0	0				0	0				0	0				0	0				0	0				0
24	HM02	0	0				0	0				0	0				0	0				0	0				0	0				0
25	HM03	0	0				0	0				0	0				0	0				0	0				0	0				0
26	HM04	0	0				0	0				0	0				0	0				0	0				0	0				0
27	HM05	0	0				0	0				0	0				0	0				0	0				0	0				0
28	HM06	0	0				0	0				0	0				0	0				0	0				0	0				0
29	PI01	50	250				0	0				0	0	10	1	2	10	20				0	0				0	0				0
30	PI02	0	0				0	0				0	0				0	0				0	0				0	0				0
31	PI03	0	0				0	0				0	0				0	0				0	0				0	0				0
32	PI04	65	0				0	0				0	0				0	0				0	0				0	0				0
33	KH01	0	0				0	0				0	0				0	0				0	0				0	0				0
34	SI01	32	0				0	0				0	0				0	0				0	0				0	0				0
35	SI02	0	0				0	0				0	0				0	0				0	0				0	0				0
36	MG01	0	0				0	0				0	0				0	0				0	0				0	0				0
37	MG02	0	0				0	0				0	0				0	0				0	0				0	0				0
38	MG03	100	0				0	0				0	0				0	0				0	0				0	0				0
39	MG04	0	0				0	0				0	0				0	0				0	0				0	0				0
40	MG05	0	0				0	0				0	0				0	0				0	0				0	0				0
41	MG06	36	0				0	0				0	0				0	0				0	0				0	0				0
42	MG07	0	0				0	0				0	0				0	0				0	0				0	0				0
43	MG08	36	108				0	0				0	0				0	0				0	0				0	0				0
44	NE01	30	210				0	0				0	0				0	0				0	0				0	0				0
45	KE01	24	144				0	0				0	0				0	0				0	0				0	0				0
46	KE02	30	180				0	0				0	0				0	0	45	1	1	450	450				0	0	10	1	1	100
		0	0				0	0				0	0				0	0				0	0				0	0				0
		0	0				0	0				0	0				0	0				0	0				0	0				0
47	GG01	0	0				0	0				0	0				0	0				0	0				0	0				0
48	GG02	0	0				0	0				0	0				0	0				0	0				0	0				0
49	GG03	0	0				0	0				0	0				0	0				0	0				0	0				0
50	GG04	0	0				0	0				0	0				0	0				0	0				0	0				0
51	GG05	0	0				0	0				0	0				0	0				0	0				0	0				0
52	RM01	0	0				0	0				0	0				0	0				0	0				0	0				0
53	RM02	30	150				0	0				0	0				0	0				0	0				0	0				0
54	RM03	0	0				0	0				0	0				0	0				0	0				0	0				0
55	RM04	0	0				0	0				0	0				0	0				0	0				0	0				0
56	RM05	0	0				0	0				0	0				0	0				0	0				0	0				0
57	RM06	0	0				0	0				0	0				0	0				0	0				0	0				0
58	RM07	0	0				0	0				0	0				0	0				0	0				0	0				0
59	PK01	100	0				0	0				0	0				0	0				0	0				0	0				0
60	PK02	120	0				0	0				0	0				0	0				0	0				0	0				0
61	PK03	0	0				0	0				0	0				0	0				0	0				0	0				0
62	PK04	0	0				0	0				0	0				0	0				0	0				0	0				0
63	PK05	0	0				0	0				0	0				0	0				0	0				0	0				0
64	PK06	0	0				0	0				0	0				0	0				0	0				0	0				0
65	MS01	30	0				0	0				0	0				0	0				0	0				0	0				0
66	MS02	0	0				0	0				0	0				0	0				0	0				0	0				0
67	MS03	0	0				0	0				0	0				0	0				0	0				0	0				0
68	MS04	0	0				0	0				0	0				0	0				0	0				0	0				0
69	DG01	0	0				0	0				0	0				0	0				0	0				0	0				0
70	DG02	100	500				0	0				0	0				0	0				0	0				0	0				0
71	DG03	0	0				0	0				0	0				0	0				0	0				0	0				0

NOTE: This is

Sl.No.	Questionaire Number		Setup Box					Water Pump					Others						Others 2						Total Wattage	Total Wh	Ranking
		Total Wh	W	No.	Hrs.	Total W	Total Wh	W	No.	Hrs.	Total W	Total Wh	Name	W	No.	Hrs.	Total W	Total Wh	Name	W	No.	Hrs.	Total W	Total Wh			
1	JA01	0	18	1	2	18	36				0	0	Speaker	10.2	1	2	10.2	20.4					0	0	97.4	180	4
2	JA02	0				0	0				0	0					0	0					0	0	6	18	
3	JA03	0	18	1	3	18	54				0	0	Others	7.2	1	3	7.2	21.6					0	0	60.9	180	4
4	JA04	0				0	0				0	0					0	0					0	0	3	9	
5	JA05	0	18	1	4	18	72				0	0					0	0					0	0	58	216	4
6	JA06	0				0	0				0	0					0	0					0	0	9	21	4
7	JA07(School)	0				0	0				0	0					0	0					0	0	0	0	
8	NC01	0	18	1	8	18	144				0	0	Speaker	3	1	8	3	24					0	0	131	632	3
9	NC02	0	18	1	3	18	54				0	0					0	0					0	0	177	501	3
10	NC03	0	18	1	3	18	54				0	0	Speaker	5	1	2	5	10					0	0	95	257	
11	HA01	0				0	0				0	0					0	0					0	0	36.9	31.8	5
12	HA02	0				0	0				0	0					0	0					0	0	6	0	5
13	HA03	0				0	0				0	0					0	0					0	0	18	18	5
14	HA04	0				0	0				0	0	Lantern	5	1		5	0					0	0	18.5	41	5
15	HA05	0	18	1	0	18	0				0	0					0	0					0	0	109	54	5
16	HA06	0	18	1	0	18	0				0	0	CFL	22	1	0	22	0					0	0	228	190	5
17	HA07	0				0	0				0	0	LED	9	1	0	9	0	Speaker	70	1	0	70	0	134	60	5
18	HA08	0				0	0				0	0	Lantern	3	1	1	3	3					0	0	52.5	17	5
19	HA09	0	18	1	0	18	0				0	0	Speaker	20	1	0	20	0					0	0	105	36	5
20	HA10	0				0	0				0	0					0	0					0	0	25.5	38.5	5
21	HA11	0	18	1	0	18	0				0	0	Speaker	50	1	4	50	200					0	0	243.2	482.4	5
22	HA12	0	18	1	0	18	0				0	0					0	0					0	0	151.5	20.5	5
23	HM01	0				0	0				0	0	CFL	15	3	0	45	0					0	0	68.6	61.2	5
24	HM02	0				0	0				0	0	LED	3	1	0	3	0					0	0	19.8	27.6	5
25	HM03	0				0	0				0	0					0	0					0	0	15	0	5
26	HM04	0				0	0				0	0					0	0					0	0	5	15	5
27	HM05	0				0	0				0	0					0	0					0	0	5	30	5
28	HM06	0				0	0				0	0					0	0					0	0	22	21	5
29	PI01	0	18	1	5	18	90				0	0					0	0					0	0	94.5	421	5
30	PI02	0				0	0				0	0					0	0					0	0	30.2	112.4	5
31	PI03	0				0	0				0	0					0	0					0	0	40	46	5
32	PI04	0	18	1	0	18	0				0	0	LED	7	2		14	0	Speaker		1		0	0	104	42	
33	KH01	0				0	0				0	0	Speaker	6	1	2	6	12					0	0	27.5	83	5
34	SI01	0	18	1	0	18	0				0	0	LED	9	1	0	9	0	Speaker	250	1		250	0	316.4	24.8	
35	SI02	0				0	0				0	0	LED	9	1	0	9	0					0	0	34	50	
36	MG01	0				0	0				0	0					0	0					0	0	7	0	3
37	MG02	0				0	0				0	0					0	0					0	0	110	40	5
38	MG03	0	18	1	0	18	0				0	0					0	0					0	0	243.5	37	
39	MG04	0				0	0				0	0					0	0					0	0	38	9	
40	MG05	0				0	0				0	0					0	0					0	0	100	0	
41	MG06	0				0	0				0	0					0	0					0	0	59.5	5.5	5
42	MG07	0				0	0				0	0					0	0					0	0	27	20	5
43	MG08	0	18	1	3	18	54				0	0					0	0					0	0	98.5	224	5
44	NE01	0	18	1	7	18	126				0	0					0	0					0	0	195	641	
45	KE01	0	18	1	6	18	108				0	0					0	0					0	0	259.5	1087	
46	KE02	100	24	1	6	24	144				0	0	Electric K	1500	1	1	1500	1500	Blender	550	1	1	550	550	2884	3594	
		0				0	0				0	0					0	0					0	0	0	0	
		0				0	0				0	0					0	0					0	0	0	0	
47	GG01	0				0	0				0	0					0	0					0	0	4.5	19	
48	GG02	0				0	0		1		0	0	LED	3	1	2	3	6					0	0	7.5	25	5
49	GG03	0				0	0		1		0	0					0	0					0	0	18	75	
50	GG04	0				0	0				0	0	LED	1	2	7	2	14					0	0	13.5	94	
51	GG05	0				0	0				0	0					0	0					0	0	4.5	19	
52	RM01	0				0	0				0	0					0	0					0	0	4.5	19	2
53	RM02	0	9	1	5	9	45				0	0	LED	3	1	3	3	9					0	0	154.5	248	
54	RM03	0				0	0				0	0					0	0					0	0	7	24	
55	RM04	0				0	0				0	0					0	0					0	0	4.5	19	2
56	RM05	0				0	0				0	0					0	0					0	0	4.5	19	0
57	RM06	0				0	0				0	0					0	0					0	0	4.5	19	2
58	RM07	0				0	0				0	0					0	0					0	0	4.5	19	
59	PK01	0	18	1	0	18	0				0	0	Fan	100	1	0	100	0					0	0	313.5	488	4
60	PK02	0				0	0				0	0	Fan	40	1	0	40	0	Cooler	40	1	0	40	0	424	1168	5
61	PK03	0				0	0				0	0	Speaker	34.5	1	1	34.5	34.5					0	0	42	54.5	5
62	PK04	0				0	0				0	0					0	0					0	0	175	700	
63	PK05	0				0	0				0	0					0	0					0	0	162	952	3
64	PK06	0				0	0				0	0					0	0					0	0	134.5	613	
65	MS01	0	18	1	0	18	0				0	0					0	0					0	0	223	530	4
66	MS02	0				0	0				0	0					0	0					0	0	5	10	
67	MS03	0				0	0				0	0					0	0					0	0	2.5	5	5
68	MS04	0				0	0				0	0					0	0					0	0	9.5	19	5
69	DG01	0				0	0				0	0					0	0					0	0	0	0	
70	DG02	0	18	1	5	18	90				0	0	LED	7	2	4	14	56	Fan	50	1	3	50	150	362.5	1325	
71	DG03	0				0	0				0	0					0	0					0	0	0	0	0

NOTE: This is

Sl.No.	Questionaire Number	Importance of Electricity					
		Remarks, if low	3 Use cases			Monthly Payment	Confidence Level
			Use case 1	Use case 2	Use case 3		
1	JA01		Fan	Light		100	3
2	JA02						
3	JA03		TV	Fan	Light	200	3
4	JA04					0	5
5	JA05		TV	Fan	Light	100	3
6	JA06		TV			200	3
7	JA07(School)						
8	NC01		TV			150	4
9	NC02		TV			200	4
10	NC03						
11	HA01		TV	Smartpho	Light and	300	4
12	HA02		TV	Light	Streetligh	200	4
13	HA03		TV	Light	Streetligh	150	4
14	HA04		TV	Light		150	5
15	HA05		TV	Carpentry		200	4
16	HA06		TV	light	Streetligh	150	3
17	HA07		TV	light	Carpentry	200	4
18	HA08		TV	Streelight	Rice cook	200	5
19	HA09		TV	Streelight	Light	150	4
20	HA10		TV	Light	Drying for	200	4
21	HA11		TV	Carpentry	Light	200	4
22	HA12		TV	Streelight		200	4
23	HM01		TV	light	Weaving	150	4
24	HM02		TV	Setup box		100	3
25	HM03		TV	light		200	2
26	HM04		TV	Light	Street Lig	200	
27	HM05		TV	Light	Phone Ch	150	4
28	HM06		Light	Light for weaving		100	2
29	PI01		TV	Light	Carpentry	200	4
30	PI02		TV	Fridge	Ricecooke	200	2
31	PI03		TV	light	Fridge	200	4
32	PI04						
33	KH01		TV	Light		300	4
34	SI01						
35	SI02		TV	Light			
36	MG01		TV	Light	Fridge	100	3
37	MG02		TV	Light	Fridge	100	3
38	MG03		TV	Light	Street Lig	200	3
39	MG04		TV	Light		200	2
40	MG05						
41	MG06		TV	Light		200	5
42	MG07		TV	Light		300	3
43	MG08		TV	Fridge	Light	300	4
44	NE01		TV	Lights		300	3
45	KE01						
46	KE02						
47	GG01						
48	GG02		TV	Fan		150	4
49	GG03		TV	Fan		400	5
50	GG04		TV	Fan			
51	GG05			Fan			
52	RM01	Cant affor	Fan			160	3
53	RM02		TV	Fan	Light	150	5
54	RM03			Fan		160	3
55	RM04	Can't afford more		Fan		120	4
56	RM05	No money to buy electricity				120	1
57	RM06	Can't afford more, fa		Fan		160	4
58	RM07						
59	PK01		TV	Fan	Light	200	4
60	PK02		TV	Fan	Cooler	300	4
61	PK03		Fan	Light		200	4
62	PK04		TV	Fan		100	2
63	PK05		Fan	Light		200	2
64	PK06		Fan	Light		300	4
65	MS01		TV	Fan	Light	200	4
66	MS02		TV	Fan	Light	200	3
67	MS03		TV	Light	fan	250	1
68	MS04		TV	Sound Am	Fan	200	3
69	DG01						
70	DG02		Fan	TV	Light	250	3
71	DG03	Does not want eletricity. Can't afford it and a street light on the si					

Appendix B

Jamupani load management code

All the code in this section has been developed by Rinald Pereira.

B.1 School arduino code:

```
#include <SD.h>
#include <Wire.h>
#include <RTClib.h>
#include <SPI.h>
 //CODE FOR SCHOOL CONTROLLLER BOARD
#define CUTOFF 30000 //time in ms power will be switched off if consumption exceeds
//MAXPOWER or if hydro voltage is below 160V
#define SAMPLE 3200.0 //number of samples of current and voltage for measurement.
//No. of cycles = SAMPLE/20
#define ADCREF 3.3 //external reference of the ADC
#define ADCSTEPS 1024.0 //resolution of the ADC
#define DIODEDROP 0.75 //forward voltage drop of the diode
#define TRANSRATIO 230.0 / 4.55 //transformer ratio
#define VREF 2.338 //zero voltage output of the hall sensor
#define RMS_CORRECTION 0.92 //correction factor
#define AVG_CORRECTION 0.77 //correction factor
#define SENSITIVITY 0.4 //Sensitivity of the hall sensor
#define MAXPOWER 240.0 //max. allowed power in W for School
RTC_PCF8523 RTC;
File logfile;
byte hydro_flag = 0, SD_flag = 0;
unsigned long flttimer[2] = {
  0,
  0
}; //School and Laptop
byte flag[2] = {
  0,
  0
```

```
}; //For school(always 0 for school and always 1 for LAPTOP) and Laptop

void setup() {
    Serial.begin(9600);
    Serial.println();
    pinMode(10, OUTPUT);
    pinMode(LED_BUILTIN, OUTPUT); //SD card check light
    Serial.println("Intializing SD card");
    if (!SD.begin(10)) {
      Serial.println("Card failed or not present");
      SD_flag = 1;
      for (int i = 0; i <= 10; i++) {
        digitalWrite(LED_BUILTIN, HIGH); // turn the LED on (HIGH is the voltage level)
        delay(100); // wait for a 100ms
        digitalWrite(LED_BUILTIN, LOW); // turn the LED off by making the voltage LOW
        delay(100);
      }
    } else {
      SD_flag = 0;
      Serial.println("Card present");
      logfile = SD.open("Control.txt", FILE_WRITE);
    }
    Wire.begin();
    if (!RTC.begin()) {
      Serial.println("RTC failed");
      logfile.println("RTC failed");
    }
    logfile.println("Date, Time, IP voltage(V), I:School(mA), PF:School, PWR:School(W),Status, I: School Secondary(mA), PF: School, PWR: School(W), Status ");
    Serial.println("Date, Time, IP voltage(V), I:School(mA), PF:School, PWR:School(W), Status, I: School Secondary(mA), PF: School, PWR: School(W), Status ");
    logfile.close(); pinMode(A0, INPUT); //Hydro voltage
    pinMode(A1, INPUT); //IP voltage
    pinMode(A2, INPUT); //School current
    pinMode(A3, INPUT); //LAP current
    for (int i = 2; i <= 6; i++) {
      pinMode(i, OUTPUT); //Jamupani, Streetlights, New Chetani, Laptop, School
      if (i < 6)
        digitalWrite(i, LOW);
      else
        digitalWrite(i, HIGH);
    }
    analogReference(EXTERNAL);
}
```

```

void loop() {
    DateTime tm;
    float input[4] = {
    0,
    0,
    0,
    0
    };
    tm = RTC.now();
    if (!SD.begin(10)) {
      Serial.println("Card failed or not present");
      SD_flag = 1;
    for (int i = 0; i <= 10; i++) {
          digitalWrite(LED_BUILTIN, HIGH); // turn the LED on (HIGH is the voltage level)
      delay(100); // wait for a 100ms
      digitalWrite(LED_BUILTIN, LOW); // turn the LED off by making the voltage LOW
      delay(100);
    }
    } else {
      SD_flag = 0;
      Serial.println("Card present");
      logfile = SD.open("Control.txt", FILE_WRITE);
    }
    Serial.print(tm.year(), DEC);
    Serial.print("/");
    Serial.print(tm.month(), DEC);
    Serial.print("/");
    Serial.print(tm.day(), DEC);
    Serial.print(", ");
    Serial.print(tm.hour(), DEC);
    Serial.print(":");
    Serial.print(tm.minute(), DEC);
    Serial.print(":");
    Serial.print(tm.second(), DEC);
    Serial.print(", ");
    if (SD_flag == 0) {
      logfile.print(tm.year(), DEC);
      logfile.print("/");
      logfile.print(tm.month(), DEC);
      logfile.print("/");
      logfile.print(tm.day(), DEC);
      logfile.print(", ");
      logfile.print(tm.hour(), DEC);
      logfile.print(":");
      logfile.print(tm.minute(), DEC);
      logfile.print(":");
      logfile.print(tm.second(), DEC);
```

```
      logfile.print(", ");
    }
    for (int i = 1; i <= 3; i++) //to measure - Hydro voltage, IP voltage, School current, Laptop
    current {
      float avgV, avgI = 0, avgP = 0, PF = 0;
      if (i < 2) //Voltage calculations
      {
        int maxvalue = 0;
        for (int j = 0; j <= SAMPLE; j++) //voltage/current measurement over 160 cycles - 3200ms
        {
          if (analogRead(i) > maxvalue)
            maxvalue = analogRead(i);
           delay(1);
        }
        input[i] = (((((maxvalue * (ADCREF / ADCSTEPS)) * (2 / sqrt(2))) + DIODEDROP) * (TRANSRATIO))); //conversion to analog value from peak value to RMS value (V)
        avgV = input[i] * sqrt(2) * 0.637; //calculation of average value of a sine wave
        Serial.print(input[i], 4);
        Serial.print(", ");
        if (SD_flag == 0) {
          logfile.print(input[i], 4);
          logfile.print(", ");
        }
        if (input[1] < (160.0)) //Hydro health check
        {
          hydro_flag = 1;
          flag[1] = 1;
        } else //Laptop flag will always be ON since we do not want to turn on that line now. Can
          change once more power is generated {
            flag[1] = 0;
            hydro_flag = 0;
          }
      } else //Current calculations
      {
        float tot_current = 0, inst_current = 0;
        for (int j = 0; j < SAMPLE; j++) //current measurement over 160 cycles = 3200ms
        {
          inst_current = (2 * analogRead(i) - (VREF * ADCSTEPS / ADCREF));
          tot_current = tot_current + sq(inst_current);
          avgI = avgI + abs(inst_current);
          delay(1);
        }
```

```
        input[i] = ((sqrt(tot_current / SAMPLE) * (ADCREF / ADCSTEPS) / SENSITIVITY) * 1000.0) / RMS_CORRECTION; //conversion to RMS current value from instantaneous to analog value (mA)
        avgI = (((avgI / SAMPLE) * (ADCREF / ADCSTEPS) / SENSITIVITY) * 1000.0) / AVG_CORRECTION; //calculation of average current in mA
        avgP = avgV * avgI;
        PF = avgP / (input[i] * input[1]);
        Serial.print(input[i], 4);
        Serial.print(", ");
        Serial.print(PF, 4);
        Serial.print(", ");
        Serial.print((input[i] * input[1] * PF), 4);
        Serial.print(", ");
        if (SD_flag == 0) {
          logfile.print(input[i], 4);
          logfile.print(", ");
          logfile.print(PF, 4);
          logfile.print(", ");
          logfile.print((input[i] * input[1] * PF / 1000.0), 4);
          logfile.print(", ");
        }
        if (flag[(i - 2)] == 0) {
          if (flttimer[(i - 2)] == 0) {
            if (hydro_flag == 1) //160V set as limit
            {
              digitalWrite((8 - i), LOW);
              flttimer[(i - 2)] = millis();
              Serial.print("Low Voltage,");
              logfile.print("Low Voltage,");
            } else {
              Serial.print("No Fault,");
              logfile.print("No Fault,");
              digitalWrite((8 - i), HIGH);
            }
          } else if ((unsigned long)(millis() - flttimer[(i - 2)] >= CUTOFF)) {
            digitalWrite((8 - i), HIGH);
            flttimer[(i - 2)] = 0;
            Serial.print("Fault cleared,");
            logfile.print("Fault cleared,");
          } else {
            Serial.print("Fault++,");
            logfile.print("Fault++,");
          }
        } else {
          digitalWrite((8 - i), LOW);
          Serial.print("Flag,");
          logfile.print("Flag,");
```

```
        }
      }
      delay(10); //switching between analog channels
    }
    Serial.println();
    logfile.println();
    logfile.close();
}
```

B.2 Household arduino code

```
/*Variables to change in the code - CUTOFF(ms), PF, HH power consumption(W) */
#include <SD.h>
#include <Wire.h>
#include <RTClib.h>
#include <SPI.h>
 // FOR TESTING CHANGE ONLY TIME
//CODE FOR HOUSEHOLD CONTOLLER
#define CUTOFF 30000 //time in milliseconds power will be switched off if consumption
//exceeds HH_evepower from 18:00-23:00
#define RMS_CORRECTION 0.92 //correction factor
#define AVG_CORRECTION 0.78 //corection factor
#define SAMPLE 800.0 //number of samples of current and voltage for measurement.
// No. of cycles = SAMPLE/20
#define ADCREF 3.3 //external reference of the ADC
#define ADCSTEPS 1024.0 //resolution of the ADC
#define DIODEDROP 0.75 //forward voltage drop of the diode
#define TRANSRATIO 230.0 / 4.8 //transformer ratio
#define VREF 0.962 //reference to the differential OPAMP
#define HH_evepower 60.0 //max. allowed power for HOUSEHOLDS in the evening
RTC_PCF8523 RTC;
File logfile;
byte SD_flag = 0;
unsigned long flttimer[5] = {
  0,
  0,
  0,
  0,
  0
};


void setup() {
  Serial.begin(9600);
  Serial.println();
```

```
  pinMode(10, OUTPUT);
  pinMode(LED_BUILTIN, OUTPUT); //SD card check light
  Serial.println("Intializing SD card");
  if (!SD.begin(10)) {
    Serial.println("Card failed or not present");
    SD_flag = 1;
    for (int i = 0; i <= 10; i++) {
      digitalWrite(LED_BUILTIN, HIGH); // turn the LED on (HIGH
         is the voltage level)
      delay(100); // wait for a 100ms
      digitalWrite(LED_BUILTIN, LOW); // turn the LED off by
         making the voltage LOW
      delay(100);
    }
  } else {
    SD_flag = 0;
    Serial.println("Card present");
    logfile = SD.open("NCMTR.txt", FILE_WRITE);
  }
  logfile.println();
  Wire.begin();
  if (!RTC.begin()) {
    logfile.println("RTC failed");
    Serial.println("RTC failed");
  }
  logfile.println("Date, Time, IP voltage(V), I:1_HH(mA),
     PF:1_HH, PWR:1_HH(W), Status,I:2_HH(mA), PF:2_HH,
     PWR:2_HH(W), Status, I:3_HH(mA), PF:3_HH,
     PWR:3_HH(W),Status,I:4_HH(mA),PF:4_HH,PWR:4_HH(W),
     Status,I:5_HH(mA), PF:5_HH,PWR:5_HH(W), Status");
  Serial.println("Date, Time, IP voltage(V), I:1_HH(mA),
     PF:1_HH, PWR:1_HH(W), Status,I:2_HH(mA), PF:2_HH,
     PWR:2_HH(W), Status, I:3_HH(mA), PF:3_HH,
     PWR:3_HH(W),Status,I:4_HH(mA),PF:4_HH,PWR:4_HH(W),Status,I:5_HH(mA),PF:5_HH,
     Status");
  logfile.close();
  pinMode(A0, INPUT); //IP voltage
  pinMode(A1, INPUT); //1_HH
  pinMode(A2, INPUT); //2_HH
  pinMode(A3, INPUT); //3_HH
  pinMode(A4, INPUT); //4_HH
  pinMode(A5, INPUT); //5_HH
  pinMode(LED_BUILTIN, OUTPUT); //SD card check light
  for (int i = 4; i <= 8; i++)
    pinMode(i, OUTPUT); //5 households
  analogReference(EXTERNAL);
}
void loop() {
  DateTime tm;
  tm = RTC.now();
```

```
float input[6] = {
  0,
  0,
  0,
  0,
  0,
  0
};
if (!SD.begin(10)) {
  Serial.println("Card failed or not present");
  SD_flag = 1;
  for (int i = 0; i <= 10; i++) {
    digitalWrite(LED_BUILTIN, HIGH); // turn the LED on (HIGH is the voltage level)
    delay(100); // wait for a second
    digitalWrite(LED_BUILTIN, LOW); // turn the LED off by making the voltage LOW
    delay(100);
  }
} else {
  SD_flag = 0;
  Serial.println("Card present");
  logfile = SD.open("NCMTR.txt", FILE_WRITE);
}
if ((tm.hour() >= 18) && (tm.hour() < 23)) //Turn on HH power only from 6PM to 11PM. FOR
// TESTING CHANGE THIS PART
{
  Serial.print(tm.year(), DEC);
  Serial.print("/");
  Serial.print(tm.month(), DEC);
  Serial.print("/");
  Serial.print(tm.day(), DEC);
  Serial.print(", ");
  Serial.print(tm.hour(), DEC);
  Serial.print(":");
  Serial.print(tm.minute(), DEC);
  Serial.print(":");
  Serial.print(tm.second(), DEC);
  Serial.print(", ");
  if (SD_flag == 0) {
    logfile.print(tm.year(), DEC);
    logfile.print("/");
    logfile.print(tm.month(), DEC);
    logfile.print("/");
    logfile.print(tm.day(), DEC);
    logfile.print(", ");
    logfile.print(tm.hour(), DEC);
    logfile.print(":");
    logfile.print(tm.minute(), DEC);
```

```
      logfile.print(":");
      logfile.print(tm.second(), DEC);
      logfile.print(", ");
    }
    for (int i = 0; i <= 5; i++) //to measure voltage and current
    {
      float avgV, avgI = 0, avgP = 0, PF = 0;
      if (i < 1) //Voltage calculations
      {
        int maxvalue = 0;
        for (int j = 0; j <= SAMPLE; j++) //voltage measurement
           over 30 cycles - 600ms
        {
          if (analogRead(i) > maxvalue)
            maxvalue = analogRead(i);
          delay(1);
        }
        input[i] = (((((maxvalue * (ADCREF / ADCSTEPS)) * (2.0 /
           sqrt(2))) + DIODEDROP) * (TRANSRATIO)));
           //conversion to analog value from peak value to RMS
           value (V)
        avgV = input[i] * sqrt(2) * 0.637; //calculation of
           average value of a sine wave
        Serial.print(input[i], 4);
        Serial.print(", ");
        if (SD_flag == 0) {
          logfile.print(input[i], 4);
          logfile.print(", ");
        }
      } else //Current calculations
      {
        float tot_current = 0;
        float inst_current = 0;
        for (int j = 0; j < SAMPLE; j++) //current measurement
           over 40 cycles = 800ms
        {
          inst_current = analogRead(i) - (VREF * ADCSTEPS /
             ADCREF); //Note: 1V(0.962V) is being subtracted as
             it is the reference voltage for the OPAMP
          tot_current = tot_current + sq(inst_current);
          avgI = avgI + abs(inst_current);
          delay(1);
        }
        input[i] = sqrt(tot_current / SAMPLE) * (ADCREF /
           ADCSTEPS) * 1000 / RMS_CORRECTION;
        //conversion to RMS current value from instantaneous to
           analog value in mA. Correction
        Factor = 0.92
        avgI = (avgI / SAMPLE) * (ADCREF / ADCSTEPS) * 1000 /
           AVG_CORRECTION; //calculation of average current in
```

```
           mA
        avgP = avgV * avgI;
        PF = avgP / (input[i] * input[0]);
        Serial.print(input[i], 4);
        Serial.print(", ");
        Serial.print(PF, 4);
        Serial.print(", ");
        Serial.print((input[i] * input[0] * PF / 1000.0), 4);
        Serial.print(", ");
        if (SD_flag == 0) {
          logfile.print(input[i], 4);
          logfile.print(", ");
          logfile.print(PF, 4);
          logfile.print(", ");
          logfile.print((input[i] * input[0] * PF / 1000.0), 4);
          logfile.print(", ");
        }
        if (flttimer[(i - 1)] == 0) {
          if ((input[i] * input[0] * PF / 1000.0) >
             (HH_evepower)) //Cutoff power
          {
            digitalWrite((9 - i), LOW);
            flttimer[(i - 1)] = millis();
            Serial.print("Fault,");
            logfile.print("Fault,");
          } else {
            Serial.print("No Fault,");
            logfile.print("No Fault,");
            digitalWrite((9 - i), HIGH);
          }
        } else if ((unsigned long)(millis() - flttimer[(i - 1)]
           >= CUTOFF)) {
          Serial.print("Fault cleared,");
          logfile.print("Fault cleared,");
          digitalWrite((9 - i), HIGH);
          flttimer[(i - 1)] = 0;
        } else {
          Serial.print("Fault++,");
          logfile.print("Fault++,");
        }
      }
      delay(10); //switching between analog channels
    }
  } else {
    for (int i = 4; i <= 8; i++) {
      Serial.print(tm.year(), DEC);
      Serial.print("/");
      Serial.print(tm.month(), DEC);
      Serial.print("/");
      Serial.print(tm.day(), DEC);
```

```
      Serial.print(", ");
      Serial.print(tm.hour(), DEC);
      Serial.print(":");
      Serial.print(tm.minute(), DEC);
      Serial.print(":");
      Serial.print(tm.second(), DEC);
      Serial.print(", ");
      digitalWrite(i, LOW);
      Serial.print("OFF, ");
      if (SD_flag == 0) {
        logfile.print(tm.year(), DEC);
        logfile.print("/");
        logfile.print(tm.month(), DEC);
        logfile.print("/");
        logfile.print(tm.day(), DEC);
        logfile.print(", ");
        logfile.print(tm.hour(), DEC);
        logfile.print(":");
        logfile.print(tm.minute(), DEC);
        logfile.print(":");
        logfile.print(tm.second(), DEC);
        logfile.print(", ");
        logfile.print("OFF, ");
      }
    }
    delay(300000); //Check every minute when not in use (Can maybe use sleep mode in the future)
  }
  Serial.println();
  logfile.println();
  logfile.close();
}
```

B.3 Streetlight arduino code

```
/*Variables to change in the code - CUTOFF(ms), PF, HH power consumption(W) */
#include <SD.h>
#include <Wire.h>
#include <RTClib.h>
#include <SPI.h>
//Code written after coming to the village based on different supplies to the village and
//school. FOR TESTING CHANGE ONLY TIME
//CODE FOR STREETLIGHT CONTROL
#define CUTOFF 30000 //time in ms power will be switched off if, consumption exceeds
//HH_evepower from 18:00-23:00
#define RMS_CORRECTION 0.92 //correction factor
```

```
#define AVG_CORRECTION 0.78 //corection factor
#define SAMPLE 800.0
//number of samples of current and voltage for measurement.
//No. of cycles = SAMPLE/20
#define ADCREF 3.3 //external reference of the ADC
#define ADCSTEPS 1024.0 //resolution of the ADC
#define DIODEDROP 0.75 //forward voltage drop of the diode
#define TRANSRATIO 230.0 / 4.8 //transformer ratio
#define VREF 0.959 //reference to the differential OPAMP
#define HH_evepower 90.0 //max. allowed power in W in the evening
RTC_PCF8523 RTC;
File logfile;
byte SD_flag = 0;
unsigned long flttimer[5] = {
  0,
  0,
  0,
  0,
  0
};

void setup() {
  Serial.begin(9600);
  pinMode(10, OUTPUT);
  pinMode(LED_BUILTIN, OUTPUT); //SD card check light
  Serial.println("Intializing SD card");
  if (!SD.begin(10)) {
    Serial.println("Card failed or not present");
    SD_flag = 1;
    for (int i = 0; i <= 10; i++) {
      digitalWrite(LED_BUILTIN, HIGH); // turn the LED on (HIGH
          is the voltage level)
      delay(100); // wait for a 100ms
      digitalWrite(LED_BUILTIN, LOW); // turn the LED off by
          making the voltage LOW
      delay(100);
    }
  } else {
    SD_flag = 0;
    Serial.println("Card present");
    logfile = SD.open("STLTMTR.txt", FILE_WRITE);
  }
  logfile.println();
  Wire.begin();
  if (!RTC.begin()) {
    logfile.println("RTC failed");
    Serial.println("RTC failed");
  }
  logfile.println("Date, Time, IP voltage(V), I:1_HH(mA),
     PF:1_HH, PWR:1_HH(W), Status,I:2_HH(mA), PF:2_HH,
```

```
      PWR:2_HH(W), Status, I:3_HH(mA), PF:3_HH,
      PWR:3_HH(W),Status,I:4_HH(mA),PF:4_HH,PWR:4_HH(W),Status,I:5_HH(mA),PF:5_HH,
      Status");
  Serial.println("Date, Time, IP voltage(V), I:1_HH(mA),
      PF:1_HH, PWR:1_HH(W), Status,I:2_HH(mA), PF:2_HH,
      PWR:2_HH(W), Status, I:3_HH(mA), PF:3_HH,
      PWR:3_HH(W),Status,I:4_HH(mA),PF:4_HH,PWR:4_HH(W),Status,I:5_HH(mA),PF:5_HH,
      Status");
  logfile.close();
  pinMode(A0, INPUT); //IP voltage
  pinMode(A1, INPUT); //1_HH
  pinMode(A2, INPUT); //2_HH
  pinMode(A3, INPUT); //3_HH
  pinMode(A4, INPUT); //4_HH
  pinMode(A5, INPUT); //5_HH
  pinMode(LED_BUILTIN, OUTPUT); //SD card check light
  for (int i = 4; i <= 8; i++)
    pinMode(i, OUTPUT); //5 households
  analogReference(EXTERNAL);
}
void loop() {
  DateTime tm;
  tm = RTC.now();
  float input[6] = {
    0,
    0,
    0,
    0,
    0,
    0
  };
  if (!SD.begin(10)) {
    Serial.println("Card failed or not present");
    SD_flag = 1;
    for (int i = 0; i <= 10; i++) {
      digitalWrite(LED_BUILTIN, HIGH); // turn the LED on (HIGH
          is the voltage level)
      delay(100); // wait for a second
      digitalWrite(LED_BUILTIN, LOW); // turn the LED off by
          making the voltage LOW
      delay(100);
    }
  } else {
    SD_flag = 0;
    Serial.println("Card present");
    logfile = SD.open("STLTMTR.txt", FILE_WRITE);
  }
  if ((tm.hour() >= 17) && (tm.hour() < 23)) //Turn on
      streetlight power only from 5PM to 11PM
  {
```

```
  Serial.print(tm.year(), DEC);
  Serial.print("/");
  Serial.print(tm.month(), DEC);
  Serial.print("/");
  Serial.print(tm.day(), DEC);
  Serial.print(", ");
  Serial.print(tm.hour(), DEC);
  Serial.print(":");
  Serial.print(tm.minute(), DEC);
  Serial.print(":");
  Serial.print(tm.second(), DEC);
  Serial.print(", ");
  if (SD_flag == 0) {
    logfile.print(tm.year(), DEC);
    logfile.print("/");
    logfile.print(tm.month(), DEC);
    logfile.print("/");
    logfile.print(tm.day(), DEC);
    logfile.print(", ");
    logfile.print(tm.hour(), DEC);
    logfile.print(":");
    logfile.print(tm.minute(), DEC);
    logfile.print(":");
    logfile.print(tm.second(), DEC);
    logfile.print(", ");
  }
  for (int i = 0; i <= 5; i++) //to measure voltage and current
  {
    float avgV, avgI = 0, avgP = 0, PF = 0;
    if (i < 1) //Voltage calculations
    {
      int maxvalue = 0;
      for (int j = 0; j <= SAMPLE; j++) //voltage measurement over 40 cycles - 800ms
      {
        if (analogRead(i) > maxvalue)
          maxvalue = analogRead(i);
        delay(1);
      }
      input[i] = (((((maxvalue * (ADCREF / ADCSTEPS)) * (2.0 / sqrt(2))) + DIODEDROP) * (TRANSRATIO))); //conversion to analog value from peak value to RMS value (V)
      avgV = input[i] * sqrt(2) * 0.637; //calculation of average value of a sine wave
      Serial.print(input[i], 4);
      Serial.print(", ");
      if (SD_flag == 0) {
        logfile.print(input[i], 4);
        logfile.print(", ");
```

```
      }
    } else //Current calculations
    {
      float tot_current = 0;
      float inst_current = 0;
      for (int j = 0; j < SAMPLE; j++) //current measurement over 40 cycles = 800ms
      {
        inst_current = analogRead(i) - (VREF * ADCSTEPS / ADCREF); //Note: 1V is being
        //subtracted as it is the reference voltage for the OPAMP
        tot_current = tot_current + sq(inst_current);
        avgI = avgI + abs(inst_current);
        delay(1);
      }
      input[i] = sqrt(tot_current / SAMPLE) * (ADCREF / ADCSTEPS) * 1000 / RMS_CORRECTION; //conversion
      // to RMS current value from instantaneous to analog value in mA. Correction
      Factor = 0.92
      avgI = (avgI / SAMPLE) * (ADCREF / ADCSTEPS) * 1000 / AVG_CORRECTION; //calculation of average current in mA
      avgP = avgV * avgI;
      PF = avgP / (input[i] * input[0]);
      Serial.print(input[i], 4);
      Serial.print(", ");
      Serial.print(PF, 4);
      Serial.print(", ");
      Serial.print((input[i] * input[0] * PF), 4);
      Serial.print(", ");
      if (SD_flag == 0) {
        logfile.print(input[i], 4);
        logfile.print(", ");
        logfile.print(PF, 4);
        logfile.print(", ");
        logfile.print((input[i] * input[0] * PF / 1000.0), 4);
        logfile.print(", ");
      }
      if (flttimer[(i - 1)] == 0) {
        if ((input[i] * input[0] * PF / 1000.0) > (HH_evepower)) //Cutoff power
        {
          digitalWrite((9 - i), LOW);
          flttimer[(i - 1)] = millis();
          Serial.print("Fault,");
          logfile.print("Fault,");
        } else {
          Serial.print("No Fault,");
```

```
              logfile.print("No Fault,");
              digitalWrite((9 - i), HIGH);
            }
          } else if ((unsigned long)(millis() - flttimer[(i - 1)]
             >= CUTOFF)) {
            Serial.print("Fault cleared,");
            logfile.print("Fault cleared,");
            digitalWrite((9 - i), HIGH);
            flttimer[(i - 1)] = 0;
          } else {
            Serial.print("Fault++,");
            logfile.print("Fault++,");
          }
        }
        delay(10); //switching between analog channels
      }
    } else {
      for (int i = 4; i <= 8; i++) {
        Serial.print(tm.year(), DEC);
        Serial.print("/");
        Serial.print(tm.month(), DEC);
        Serial.print("/");
        Serial.print(tm.day(), DEC);
        Serial.print(", ");
        Serial.print(tm.hour(), DEC);
        Serial.print(":");
        Serial.print(tm.minute(), DEC);
        Serial.print(":");
        Serial.print(tm.second(), DEC);
        Serial.print(", ");
        digitalWrite(i, LOW);
        Serial.print("OFF, ");
        if (SD_flag == 0) {
          logfile.print(tm.year(), DEC);
          logfile.print("/");
          logfile.print(tm.month(), DEC);
          logfile.print("/");
          logfile.print(tm.day(), DEC);
          logfile.print(", ");
          logfile.print(tm.hour(), DEC);
          logfile.print(":");
          logfile.print(tm.minute(), DEC);
          logfile.print(":");
          logfile.print(tm.second(), DEC);
          logfile.print(", ");
          logfile.print("OFF, ");
        }
      }
      delay(300000); //Check every minute when not in use (Can
         maybe use sleep mode in
```

```
    // the future)
  }
  Serial.println();
  logfile.println();
  logfile.close();
}
```

B.4 Datalogging arduino code

```
#include <SD.h>
#include <Wire.h>
#include <RTClib.h>
#include <SPI.h>
#define MEAS_INTERVAL 1000 //time in ms between power measurements
#define SAMPLES 100 //Number of voltage/current samples
#define ADCREF 5.0 //external reference of the ADC
#define ADCSTEPS 1024.0 //resolution of the ADC
#define VREF 1.25 //reference to the differential OPAMP
#define GAIN 100.0 //OPAMP gain
RTC_PCF8523 RTC;
File logfile;
byte SD_flag = 0;
void setup() {
  Serial.begin(9600);
  Serial.println();
  pinMode(10, OUTPUT);
  pinMode(LED_BUILTIN, OUTPUT); //SD card check light
  Serial.println("Intializing SD card");
  if (!SD.begin(10)) {
    Serial.println("Card failed or not present");
    SD_flag = 1;
    for (int i = 0; i <= 10; i++) {
      digitalWrite(LED_BUILTIN, HIGH); // turn the LED on
      delay(100); // wait for a 100ms
      digitalWrite(LED_BUILTIN, LOW); // turn the LED off
      delay(100);
    }
  } else {
    SD_flag = 0;
    Serial.println("Card present");
    logfile = SD.open("Gen.txt", FILE_WRITE);
  }
  logfile.println();
  Wire.begin();
  if (!RTC.begin()) {
    logfile.println("RTC failed");
    Serial.println("RTC failed");
  }
```

```
  logfile.println("Date, Time, Battery Voltage(V), PV voltage(V), PV current(A), Hydro current(A), Charge controller-Battery current(A), Battery-Inverter current(A)");
  Serial.println("Date, Time, Battery Voltage(V), PV voltage(V), PV current(A), Hydro current(A), Charge controller-Battery current(A), Battery-Inverter current(A)");
  logfile.close();
  pinMode(A0, INPUT); //Battery voltage
  pinMode(A1, INPUT); //PV voltage
  pinMode(A2, INPUT); //PV current
  pinMode(A3, INPUT); //Hydro current
  pinMode(A4, INPUT); //CC-Battery current
  pinMode(A5, INPUT); //Battery-Inverter current
  pinMode(LED_BUILTIN, OUTPUT); //SD card check light
  analogReference(DEFAULT);
}
Design and installation of a smart control system
for a microgrid
93 void loop() {
  DateTime tm;
  tm = RTC.now();
  float input[6] = {
    0,
    0,
    0,
    0,
    0,
    0
  };
  if (!SD.begin(10)) {
    Serial.println("Card failed or not present");
    SD_flag = 1;
    for (int i = 0; i <= 10; i++) {
      digitalWrite(LED_BUILTIN, HIGH); // turn the LED on (HIGH is the voltage level)
      delay(100); // wait for a second
      digitalWrite(LED_BUILTIN, LOW); // turn the LED off by making the voltage LOW
      delay(100);
    }
  } else {
    SD_flag = 0;
    Serial.println("Card present");
    logfile = SD.open("Gen.txt", FILE_WRITE);
  }
  Serial.print(tm.year(), DEC);
  Serial.print("/");
  Serial.print(tm.month(), DEC);
  Serial.print("/");
```

```
  Serial.print(tm.day(), DEC);
  Serial.print(", ");
  Serial.print(tm.hour(), DEC);
  Serial.print(":");
  Serial.print(tm.minute(), DEC);
  Serial.print(":");
  Serial.print(tm.second(), DEC);
  Serial.print(", ");

  if (SD_flag == 0) {
    logfile.print(tm.year(), DEC);
    logfile.print("/");
    logfile.print(tm.month(), DEC);
    logfile.print("/");
    logfile.print(tm.day(), DEC);
    logfile.print(", ");
    logfile.print(tm.hour(), DEC);
    logfile.print(":");
    logfile.print(tm.minute(), DEC);
    logfile.print(":");
    logfile.print(tm.second(), DEC);
    logfile.print(", ");
  }
  for (int i = 0; i <= 5; i++) //to measure voltage and current
  {
    float total = 0.0;
    for (int j = 0; j < SAMPLES; j++)
      total += analogRead(i);
    switch (i) {
    case 0:
      input[i] = (total / SAMPLES) * (ADCREF / ADCSTEPS) *
         (115.0 / 15.0); //Resistor divider network R1=100kohm,
         R2=15kohm
      break;
    case 1:
      input[i] = (total / SAMPLES) * (ADCREF / ADCSTEPS) *
         (165.0 / 15.0); //Resistor divider network R1=150kohm,
         R2=15kohm
      break;
    case 2:
      input[i] = (total / SAMPLES) * (ADCREF / ADCSTEPS) / (GAIN
         * 0.001); // Sense resistor=1mohm
      break;
    case 3:
      input[i] = (total / SAMPLES) * (ADCREF / ADCSTEPS) / (GAIN
         * 0.001); //Sense resistor=1mohm
      break;
    case 4:
      input[i] = (((total / SAMPLES) * (ADCREF / ADCSTEPS)) -
         VREF) / (GAIN * 0.0005); //Sense resistor=0.5mohm
```

```
      break;
    case 5:
      input[i] = (total / SAMPLES) * (ADCREF / ADCSTEPS) / (GAIN * 0.0005); //Sense resistor=0.5mohm
      break;
    }
    Serial.print(input[i], 4);
    Serial.print(", ");
    if (SD_flag == 0) {
      logfile.print(input[i], 4);
      logfile.print(", ");
    }
    delay(10); //switching between analog channels
  }
  Serial.println();
  logfile.println();
  logfile.close();
  delay(MEAS_INTERVAL);
}
```

Appendix C

Jamupani microgrid checklists

C.1 Jamupani microgrid weekly checklist

Hydropower checklist:

1. Clear all of the debris in the net at the input in the river.
2. Check if the water is continuously coming to the water tank. Make sure the input water is overflowing from the tank.
3. Check if the input to the hydropower pipe (HDPE/rubber pipe) in the tank do not have any blockage.
4. Remove the sediments from the tank using the drain pipe.
5. Check for any leakages in the HDPE pipe. If there are leakage, lay the pipe and try to remove or reduce leakages.
6. Check for any breakage or bent in the HDPE pipe.
7. Check the pressure level in the nozzle of the turbine. The pressure level should be more than 1.2 Kg/cm2.
8. Switch off the MCB and check the display of the turbine. You should see the following data:
    - Voltage level: 230 to 250 V
    - Frequency: 48 to 52
    - P level: P022 to P028
9. Switch on the MCB. You should see the following data:
    - Voltage level:200 to 250 V
    - Frequency: 48 to 52
    - P level: P000 to P028
10. Make sure the connection from hydropower to the input wire is connected well.

Checklist in the control room:

1. Using tester check if power is coming to the MCB from hydropower.
2. Using tester check if the power is going to the school from the School Primary RCBO. Make sure the School Primary RCBO is switched on.
3. Check if the solar panels is charging the batteries. Look at the display in the charge controller to see if charging is happening.

4. Check if all of the battery connection is correct. Look for loose wires and connect them properly.
5. Check if the inverter is providing power to the Jamupani RCBO.
6. Using tester check if the power is going to the village from the Jamupani RCBO. Make sure the Jamupani RCBO is switched on.
7. Make sure all of the wiring is proper. If there are any loose connections, correct it.
8. Make sure the control room is locked properly. Close the window and the door properly.

C.2 Jamupani microgrid monthly checklist

Hydropower checklist:

1. Clear all of the debris in the net at the input in the river.
2. Check the GI pipes at every joint. Make sure the pipe is laid properly. Check if all of the supports to the pipe are in place.
3. Check for any damages to the GI pipe. If there are damages, either rectify it or change the pipe section with spare pipes.
4. Make sure the water is continuously flowing to the water tank. The water should be overflowing from the tank after 15 minutes of connecting the GI pipe to the inlet. If not, conduct the following test:
    - Make sure the entire GI pipe inlet is submerged in the water at the river.
    - Remove any debris, stones or particles in front of the inlet or the net.
    - Check for leakages in pipe.
    - Even after conducting above checks, if water is not flowing to the tank, it is likely that some section of the pipe is blocked. Blockage needs to be removed by disconnecting and connecting different section of the pipe.
5. Check if the input to the hydropower pipe (HDPE/rubber pipe) in the tank do not have any blockage.
6. Remove the sediments from the tank using the drain pipe.
7. Close the tank properly using tin sheets. Make sure no leaves or external particles can get inside the tank.
8. Check for any damages to the tin sheets. If any, rectify it or replace the tin sheets.
9. Check every section of the HDPE pipe for leakages and damages. Give special care to the joints. They are the likely source for leakages or damages. If there are damages or leakages in the pipe, try to rectify by properly laying the pipe or by replacing the pipe section.
10. If in case any HDPE pipe section needs replacement, make sure the washers for the joints are kept properly.
11. Check every support element of the pipe. Make sure there are no changes to the support.
12. Look for negative heads and correct if any.
13. Check the pressure level in the nozzle of the turbine. The pressure level should be more than 1.2 Kg/cm2.

14. Switch off the MCB and check the display of the turbine. You should see the following data:
    - Voltage level: 230 to 250 V
    - Frequency: 48 to 52
    - P level: P022 to P028
15. Switch on the MCB. You should see the following data:
    - Voltage level: 230 to 250 V
    - Frequency: 48 to 52
    - P level: P000 to P028
16. If after switching off, the frequency level or voltage drops below the mentioned numbers, the hydropower is overloaded. Make sure to switch off some of the appliances/lights.
17. Make sure the connection from hydropower to the input wire is connected well.
18. Check the wire from the hydropower to the control board for any damages or wire sag.

Checklist in the control room:

1. Using tester check if power is coming to the MCB from hydropower.
2. Using tester check if the power is going to the school from the SCHOOL RCBO. Make sure the SCHOOL RCBO is switched on.
3. Check if the solar panels are in place. If not, fix the position properly.
4. Check the connections of panels to the connector box. Check the connection from connector box to the charge controller.
5. Check the connection from the charge controller to the batteries.
6. Check if the solar panels is charging the batteries. Look at the display in the charge controller to see if charging is happening.
7. Check the battery connections.
8. Check the amount of distilled water in the batteries. If it is below recommended level (marked in the batteries), top-up the distilled water.
9. Check if the inverter is providing power to the Jamupani control board.
10. Using tester check if the power is going to the village from the Jamupani RCBO. Make sure the Jamupani RCBO is switched on.
11. Make sure all of the wiring is proper. If there are any loose connections, correct it.
12. Check if the lightning rod is in place. Check if the earthing cable is connected to the lightning rod.
13. Check earthing connection from the inverter to the earthing connection plate (neutral patti).
14. Check if the earthing connection out from the neutral patti is going to the earthing pit.
15. Make sure the control room is locked properly. Close the window and the door properly.

Bibliography

[1] A. Doukas and A. Ballesteros. "Clean Energy Access in Developing Countries: Perspectiveson Policy and Regulation". In: *World Resour. Inst. Keys To Achiev. Univers. Energy Acces Ser.* 2015.

[2] J. Sumanik-Leary et al. *Engineering in Development - Energy*. Engineers Without Borders UK. London, England: Engineers Without Borders UK, 2014.

[3] S. Thomson. *What are the Sustainable Development Goals?* URL: `https://www.weforum.org/agenda/2015/09/what-are-the-sustainable-development-goals`.

[4] *WEO-2017 Special Report: Energy Access Outlook*. OECD/International Energy Agency. 2017. URL: `https://webstore.iea.org/weo-2017-special-report-energy-access-outlook`.

[5] *Tracking SDG7: The energy progress report 2019*. The World Bank. 2019. URL: `https://trackingsdg7.esmap.org/data/files/download-documents/2019-Tracking%5C%20SDG7-Full%5C%20Report.pdf`.

[6] S. D. D'Cunha. *Modi Announces '100% Village Electrification', But 31 Million Indian Homes Are Still In The Dark*. URL: `https://www.forbes.com/sites/suparnadutt/2018/05/07/modi-announces-100-village-electrification-but-31-million-homes-are-still-in-the-dark/`.

[7] The World Bank. *Access to electricity, rural (% of rural population).* URL: `https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS`.

[8] T. S. Ustun F. Almeshqab. "Lesons learned from rural electrification initiatives in developing countries: Insights for technical, social, financial and public policy aspects". In: *Renewable and Sustainable Energy Reviews*. 2019, pp. 35–54.

[9] International Renewable Energy Agency (IRENA). *Off-grid renewable energy solutions to expand electricity access: An opportunity not to be missed*. URL: `https://www.irena.org/publications/2019/Jan/Off-grid-renewable-energy-solutions-to-expand-electricity-to-access-An-opportunity-not-to-be-missed`.

[10] S. Ghosh et al. *Power for All: Electricity Access Challenge in India*. The World Bank. Washington DC, United States, 2015.

[11] International Renewable Energy Agency (IRENA). *Off-grid Renewable Energy Solutions: Global and Regional Status and Trends*. URL: `www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jul/IRENA_Off-grid_RE_Solutions_2018.pdf`.

[12] M. Yaqoot et al. “Review of barriers to the dissemination of decentralized renewable energy systems”. In: *Renewable and Sustainable Energy Reviews* 58 (2016), pp. 477–490. DOI: `http://dx.doi.org/10.1016/j.rser.2015.12.224`.

[13] H. J. Corsair. *Causes of Success and Failure of Stand-alone Solar Electric Systems in Rural Guatemala*. Doctoral dissertation. Johns Hopkins University. Maltimore, Maryland, United States: Johns Hopkins University, 2013.

[14] N. Bali S. Agrawal and J. Urpelainen. *Rural electrification in India: Customer behaviour and demand*. The Rockefeller Foundation. 2019. URL: `https://assets.rockefellerfoundation.org/app/uploads/20190219123625/Rural-Electrification-in-India-Customer-Behaviour-and-Demand.pdf`.

[15] *Sustainable Development Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all*. United Nations, Inter-Agency and Expert Group on SDG Indicators. 2015. URL: `https://sustainabledevelopment.un.org/sdg7`.

[16] D. Lecoque. *Rural Electrification*. Alliance for Rural Electrification. 2019. URL: `https://www.ruralelec.org/rural-electrification`.

[17] Sustainable Energy for All (SE4ALL) database. *Acces to electricity, urban, world*. The World Bank. 2020. URL: `https://data.worldbank.org/indicator/EG.ELC.ACCS.UR.ZS`.

[18] Jr. W.D Devine. *From Shafts to Wires: Historical Perspective on Electrification*. Journal of Economic History. 1983. URL: `https://web.archive.org/web/20190412093317/http://www.j-bradford-delong.net/teaching_folder/Econ_210c_spring_2002/Readings/Devine.pdf`.

[19] Sustainable Energy for All (SE4ALL) database. *Acces to electricity, rural, India*. The World Bank. 2020. URL: `https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS?locations=IN`.

[20] Sustainable Energy for All (SE4ALL) database. *Acces to electricity, urban, India*. The World Bank. 2020. URL: `https://data.worldbank.org/indicator/EG.ELC.ACCS.UR.ZS?locatoins=IN`.

[21] M.A. Toman J. Peters M. Sievert. “Rural Electrification through Mini-Grids: Challenges Ahead”. In: *Leibniz-Institut für Wirtschaftsforschung*. 2018.

[22] “A Review of Power Management and Stability Issues in Microgrid”. In: 2016.

[23] Economic Times Bureau. *Government launches Saubhagya scheme for household electrification*. The Economic Times. 2020. URL: `https://economictimes.indiatimes.com/news/economy/policy/government-launches-saubhagya-scheme-for-household-electrification/articleshow/60828887.cms`.

[24] Anaya Singh Sanjay Kumar. *Shedding light on Saubhagya: on electrification scheme*. The Hindu. 2020. URL: `https://www.thehindu.com/opinion/op-ed/shedding-light-on-saubhagya/article19913598.ece`.

[25] *Rural electrification policy, 2006*. International Environmental Law Research Centre. 2006. URL: `http://www.ielrc.org/content/e0639.pdf`.

[26] Google. *Scribble Maps: Nepal*. Google. 2017. URL: `https://www.scribblemaps.com/create/%5C#lat=28.394857%5C&lng=84.124008%5C&z=7`.

[27] M. Islar et al. “Feasibility of energy justice: Exploring national and local efforts for energy development in Nepal”. In: *Energy Policy* 150 (2017), pp. 668–676.

[28] S. Pokharel. “An econometric analysis of energy consumption in Nepal”. In: *Energy Policy* 35 (2007), pp. 350–361.

[29] B.B. Pradhan and B. Limmeechokchai. “Electric and Biogas Stoves as Options for Cooking in Nepal and Thailand”. In: *Energy Procedia* 138 (2017), pp. 470–475.

[30] R. Nepal. “Roles and potentials of renewable energy in less-developed economies”. In: *Renewable and Sustainable Energy Reviews* 16 (2012), pp. 2200–2206.

[31] *How much electricity does an American home use?* U.S. Energy Information Administration. 2017. URL: `https://www.eia.gov/tools/faqs/faq.php?id=97%5C&t=3`.

[32] R. White. “GEF-FAO Workshop on Productive Uses of Renewable Energy: Experience, Strategies, and Project Development”. In: *Workshop Synth. Rep.* UNFood Agric. Organ. Rome, Italy, June 2002.

[33] R. Anil Cabraal et. al. “Productive Use of Energy for Rural Development”. In: *Annu. Rev. Environ. Resour.* 2005.

[34] The World Bank. *Beyond Connections - Energy Access Redefined*. The World Bank ESMAP Programme. The World Bank, 2015.

[35] C Blodgett et al. “Accuracy of energy-use surveys in predicting rural mini-grid user consumption”. In: *Energy for Sustainable Development*. Dec. 2017.

[36] *Smart Power Connect May 2017*. Rockerfeller Foundation. 2017. URL: `https://www.rockefellerfoundation.org/report/smart-power-connect-may-2017/`.

[37] S. Ali R. Bhoi. *Potential of Hydro Power in India and its Impacts on Environment*. IJETT, 2014.

[38] D. Lodrick. *Encyclopaedia Britannica - Arunachal Pradesh*. Encyclopedia Britannica, 2018. URL: `https://www.britannica.com/place/Arunachal-Pradesh`.

[39] R. Marthur. *Encyclopaedia Britannica - Uttar Pradesh*. Encyclopedia Britannica, 2018. URL: `https://www.britannica.com/place/Uttar-Pradesh`.

[40] *2017, Social Demography*. Government of Uttar Pradesh, 2017. URL: `up.gov.in/Social-Demography.pdf`.

[41] *India’s per capita income grows by 8.6% to Rs 1.13 lakh in FY18*. The Times of India, 2018. URL: `https://timesofindia.indiatimes.com/business/india-business/indias-per-capita-income-grows-by-8-6-to-rs-1-13-lakh-in-fy18/articleshow/64403580.cms`.

[42] *Flaticon free vector images*. Freepik Company S.L., 2018. URL: `https://www.flaticon.com`.

[43] Government of India Office of the Registrar General & Census Commissioner Ministry of Home Affairs. “HH10: Hoseholds by availability of separate kitchen and type of fuel used for cooking”. In: *Indian Census 2011*. 2011.

[44] *Providing Clean Cooking Fuel in India: Challenges and solutions*. The International Institute for Sustainable Development, Integrated Research, and Action for Development (IRADe). 2016.

[45] A. White K.L. Barriball. "Collecting data using a semi-structured interview: a discussion paper". In: *Journal of Advanced Nursing* 19 (1994), pp. 328–335. DOI: `10.1111/j.1365-2648.1994.tb01088.x`.

[46] P. Kumar D.F. Barner and K. Openshaw. *Cleaner hearths, better homes - New stoves for India and the developing world*. The World Bank. 2012. URL: `https://www.cleancookingalliance.org/resources_files/cleaner-hearths-better.pdf`.

[47] R.C. Sethi A.P. Singh and C. Chandramouli. *Census of India 2011 - Administrative Atlas of India*. Office of the Registrar General & Census Commissioner & Ministry of Home Affairs, Government of India. 2011.

[48] *India Cookstoves and Fuels Market Assessment*. Global Alliance for Clean Cookstoves. 2013. URL: `http://cleancookstoves.org/resources_files/india-cookstove-and-fuels-market-assessment.pdf`.

[49] L.M. Mildner. *Clean cooking in India - Reasons for lacking adoption of clean cooking technologies at household level*. Master's Thesis. Technical University of Munich. 2018.

[50] S.C. Anenberg et al. "Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls". In: *Environmental Health Perspectives* 120(6) (2012), p. 831. DOI: `10.1289/ehp.1104301`.

[51] G. Shrimali et al. "Improved stoves in India: A study of sustainable business models". In: *Energy Policy* 39(12) (2011), pp. 7543–7556. DOI: `https://doi.org/10.1016/j.enpol.2011.07.031`.

[52] N. Schlag and F. Zuzarte. *Market Barriers to Clean Cooking Fuels in Sub-Saharan Africa - A Review of Literature*. Stockholm Environment Institute. 2008.

[53] M. Khandelwal et al. "Why Have Improved Cook-Stove Initiatives in India Failed?" In: *World Development* 92 (2017), pp. 13–27. DOI: `https://doi.org/10.1016/j.worlddev.2016.11.006`.

[54] E.M. Rogers. *Diffusion of innovation (5th ed.)* Free Press, New York, 2003.

[55] J.J. Lewis et al. "Piloting improved cookstoves in India". In: *Journal of health communication* 20(sup1) (2015), pp. 28–42.

[56] S.S. Mathur S.A. Quadir and T.C. Kandpal. "Barriers to dissemination of renewable energy technologies for cooking". In: *Energy Conversion and Management* 36(12) (1995), pp. 1129–1132. DOI: `https://doi.org/10.1016/0196-8904(95)00009-3`.

[57] R.C. Duncan. *Rationalising Subsidies, Reaching the Underserved - Improving Effectiveness of Domestic LPG Subsidy and Distribution in India*. Council on Energy, Environment and Water. 2014.

[58] V.L. Pandey and A. Chaubal. "Comprehending household cooking energy choice in rural India". In: *Biomass and Bioenergy* 35(11) (2011), pp. 4724–4731. DOI: `https://doi.org/10.1016/j.biombioe.2011.09.020`.

[59] N. Aveñando García et al. *Zonas no interconectadas - ZNI: diagnóstico de la prestación del servicio de energía eléctrica*. Superintendencia de servicions públicos domiciliarios de Colombia. 2018. URL: https://www.superservicios.gov.co/sites/default/archivos/Publicaciones/Publicaciones/2018/Dic/diag_zni_2018_7122018.pdf.

[60] Sustainable Energy for All (SE4ALL) database. *Acces to electricity, Latin America and the Caribbean*. The World Bank. 2020. URL: https://data.worldbank.org/indicator/EG.ELC.ACCS.UR.ZS?locatoins=ZJ.

[61] *Boletín estadístico de Minas y Energía 2018*. Unidad de Planeación Minero-Energética (UPME). Ministerio de Minas y Energía, 2018.

[62] C. Trujillo E. Gaona and J. Guacaneme. "Rural microgrids and their potential application in Colombia". In: *Renewable and Sustainable Energy Reviews* 51 (2015), pp. 125–137. DOI: doi.org/10.1016/j.rser.2015.04.176.

[63] *Integración de las energías renovables no convencionales en Colombia*. Unidad de Planeación Minero-Energética (UPME). Ministerio de Minas y Energía, 2015.

[64] S. Morales et al. *An overview of small hydropower plants in Colombia: Status, potential, barriers and perspectives*. Organisation for Economic Co-operation and Development. OECD Economic Surveys – Colombia, 2017. URL: www.oecd.org/eco/surveys/economic-survey-colombia.htm.

[65] N. Mora-Guarda. *Socio-economic determinants for the implementation of renewable energy systems in off-grid areas of Colombia*. Master's Thesis. Technical University of Munich. 2019.

[66] R. Ortiz et al. *Recommendations for institutional electric sector reform for non-interconnected areas*. 2019.

[67] T. Gomez-Navarro and D. Ribo-Perez. "Assessing the obstacles to the participation of renewable energy source in the electricity market of Colombia". In: *Renewable and Sustainable Energy Reviews* 90 (2018), pp. 131–41. DOI: https://doi.org/10.1016/j.rser.2018.03.015.

[68] *Transforming our world : the 2030 Agenda for Sustainable Development*. United Nations. 2015. URL: https://www.refworld.org/docid/57b6e3e44.html.

[69] *Zonas No Interconectadas – ZNI. Diagnostico de la prestación del servicio de energía eléctrica 2019*. Super Intendencia de Servicios Publicos Domiciliarios (SSPD). 2019. URL: https://www.superservicios.gov.co/sites/default/archivos/Publicaciones/Publicaciones/2019/Dic/diagnostico_de_la_prestacion_del_servicio_zni_-_07-11-2019-lo_1.pdf.

[70] M. Cabarcas. *Pobreza extrema en Colombia se centra en más del 50% en el Chocó y el Caribe*. RCN Radio. 2018. URL: https://www.rcnradio.com/colombia/pobreza-extrema-en-colombia-se-centra-en-mas-del-50-en-el-choco-y-el-caribe.

[71] J. Tarazona. *Se agrava crisis humanitaria en el Chocó*. 2019. URL: https://www.rcnradio.com/colombia/pacifico/se-agrava-crisis-humanitaria-en-el-choco.

[72] IEEE Power & Energy Society. “IEEE recommended practice for monitoring electric power quality”. In: *IEEE Std 1159TM-2009* (2009).

[73] R.C. Duncan. *Electrical Power System Quality*. McGraw-Hill, 2003.

[74] A. von Meier. *Electric Power Systems*. John Wiley & Sons, Inc., 2006.

[75] et al. A.K.Seppälä. “Simple Regression Model for Energy Demand: Case Study in Rural Areas of Nepal”. In: *5th International Conference on the Developments in Renewable Energy Technology (ICDRET’18)* (2018).

[76] C.M. Colson and M.H. Nehrir. “A review of challenges to real-time power management of microgrids”. In: *!EEE Power & Energy Society General Meeting*. 2009.

[77] “Peer-to-peer control of microgrids”. In: 2016.

[78] K. Strunz et al. M.H. Nehrir C. Wang. “A Review of Hybrid Renewable/Alternative Energy Systems for Electric Power Generation: Configurations, Control, and Applications”. In: *IEEE Transactions on Sustainable Energy*. Nov. 2011, pp. 392–403.

[79] “To Centralize or to Distribute: That Is the Question: A Comparison of Advanced Microgrid Management Systems”. In: 2018.

[80] C.A. Cañizares et al. “Trends in microgrid control”. In: *IEEE Transactions on Smart Grid*. July 2014.

[81] M. Benbouzid M. F. Zia and E. Elbouchikhi. “Microgrids energy management systems: A critical review on methods, solutions, and prospects”. In: *Applied Energy*. June 2018.

[82] “Dynamic consensus algorithm based distributed global efficiency optimization of a droop controlled dc microgrid”. In: 2014.

[83] L Meng et al. “Microgrid supervisory controllers and energy management systems: A literature review”. In: *Renewable and sustainable energy reviews*. 2016, pp. 1263–1273.

[84] S. Dragićević and M. Bojić. “Application of linear programming in energy management”. In: *Serbian journal of management*. Oct. 2009.

[85] G. Graditi et al. M.L. Di Silverstre. “Robust multi-objective optimal dispatch of distributed energy resources in micro-grids”. In: *IEEE Trondheim PowerTech*. Sept. 2011.

[86] B. J. Saharia. “A review of algorithms for control and optimization for energy management of hybrid renewable energy systems”. In: *Journal of Renewable and Sustainable Energy*. Oct. 2018.

[87] Y.E. García Vera et al. “Energy Management in Microgrids with Renewable Energy Sources: A Literature Review”. In: *Applied Sciences*. July 2019.

[88] L. Olatomiwa et al. “Energy management strategies in hybrid renewable energy systems: A review”. In: *Renewable and sustainable energy reviews*. 2016, pp. 821–835.

[89] L. Wang. *Model Predictive Control System Design and Implementation Using MATLAB*. School of Electrical and Computer Engineering, RMIT University. Springer-Verlag London Limited, 2009.

[90] R. Pereira. *Design and installation of a smart control system for a microgrid*. Master’s Thesis. Technical University of Munich. 2019.

[91] J. Baek S. Oh S. Chae and M. Cook. “Efficient model predictive control strategies for resource management in an islanded microgrid”. In: *Energies*. 2017, pp. 821–835.

[92] *Google Earth Satellite Image of Jamupani*. Google Earth. 2019. URL: `https://earth.google.com/web/@28.3125556,95.9986667,684.52900604a,917.90731893d,35y,0h,0t,0r`.

[93] N.R. Gaihre. *Design and development of a hybrid micro-grid for Jamupani, India*. Master’s Thesis. Technical University of Munich. 2019.

[94] *Wire Gauge and Current Limits Including Skin Depth and Strength*. PowerStream. 2019. URL: `https://www.powerstream.com/Wire_Size.htm`.

[95] Helukabel. *Formulas of power engineering*. 2019. URL: `http://www.helukabel.com/media/publication/de/cor_docs/qt_23/QT_COR-DOCS_X_108_Formulas_of_power_engineering.pdf`.

[96] *Hydropower basics: Measurement of head*. microhydropower. 2017. URL: `http://microhydropower.net/basics/head.php#tube`.