Department of Mechanical and Aerospace Engineering

Applying multi-criteria decision methods to the selection of renewable energy technologies for a Nepalese mini-grid

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Abstract

Despite large hydro resources, Nepal has experienced widespread blackouts and unreliable electrical supplies in recent years, with the majority of the rural and remote communities still lacking an electrical connection. The government has put in place a series of policies to remedy this, including a grid extension program. This has been shown to be costly and ineffective, particularly since the grid cannot support the consumers it already serves.

Mini-grids have been shown to be an effective alternative and are the World Bank's principal method of rural electrification worldwide. This project outlines a method for selecting the renewable generation that will supply these mini-grids, by examining the case study of Jiri in Nepal. This investigation employed a combination of the analytic hierarchy process (AHP) and simulation of the system in HOMER. The number of experts consulted for the AHP method was ten, comprising engineers, NGO workers and project managers.

This project determined the most favourable system to be a hybrid of hydro, solar and biomass generation with battery storage. The system was ranked the most favourable by the respondents, who often had conflicting views when ranking criterion importance. The system was then examined in detail to confirms its suitability and that it met the key criteria of minimal cost, reliability of the supply, the greenhouse gas emissions, the risk of theft to the system and the ease of transporting and installing the system.

This investigation presents an innovative approach to renewable energy technology selection, utilising a combined AHP and simulation-based approach. This builds on previous work in the literature to provide quantifiable judgements in the decision-making process. The most highly ranked system contained a biomass generator, showing it is important to consider the local needs and available resources.

Contents

Abstract 2
List of Figures 4
List of Tables 5
1 Problem description 6
1.1 Aim 6
1.2 Objectives 6
1.3 Outline of methods 7
1.4 Structure 7
2 Literature Review 8
2.1 National background 8
2.2 Geography 8
2.2.1 Site selection 9
2.3 Political unrest 10
2.4 Economy 10
2.5 Current energy system 11
2.6 National electricity grid 11
2.6.1 Grid stability 11
2.6.2 Indian interconnection 12
2.6.3 Grid extension program 13
2.7 Mini-grids 15
2.7.1 Grid stability 15
2.7.2 Natural disasters 15
2.7.3 Cybersecurity 16
2.8 Renewable energy technologies 16
2.8.1 Hydroelectric 16
2.8.2 Wind 17
2.8.3 Solar 17
2.8.4 Bio-energy 18
2.8.5 Generation potential 18
2.8.6 Storage 19
2.9 Barriers to renewable energy uptake 19
2.9.1 Social barriers 19
2.9.2 Political and policy barriers 20
2.9.3 Economic barriers 20
2.9.4 Administrative barriers 21
2.9.5 Geographic barriers 21

2.10 Effects of climate change 21
2.11 Finance 22
2.11.1 Subsidies and incentives 23
2.12 Multi-criteria decision methods 24
2.12.1 Analytic Hierarchy Process 24
3 Methods 25
3.1 Simulations 25
3.1.1 Modelling tool selection 25
3.1.2 Demand profile 26
3.1.3 Resource prediction 26
3.1.4 System design 28
3.2 AHP for system selection 29
3.2.1 Scenarios .... **Error! Bookmark not defined.**
4 Results 30
5 Discussion 34
6 Conclusions 36
7 References 37

List of Figures

Figure 1 Land use map of Nepal [23] 9
Figure 2 The settlement of Jiri, located 85km east of Kathmandu 9
Figure 3 The current electrical generation in Nepal [27] 11
Figure 4 Nepal's electricity system load curve for 11th November 2015. The independent power producers (IPP) are presented in blue and the unmet demand resulted in load shedding. (Figure reproduced from NEA, 2016) [30] 12
Figure 5 Map of national grid extensions [29] 14
Figure 6 Map of Nepal showing fault lines in red and the 2015 earthquake epicentre north west of Kathmandu 16
Figure 7 Wind speed data for Nepal [52] 17
Figure 8 Current sources of non-renewable energy [39] 18
Figure 9 Characteristic daily demand profiles for month 26
Figure 10 Solar radiation profile 27
Figure 11 Wind resource profile 27
Figure 12 Mean stream flow of Tamakoshi river [108] 28
Figure 13 System schematic for simulations 28

Figure 14 Hierarchical structure of the process 29
Figure 15 Monthly electrical production 32
Figure 16 Proportion of generation by source 32
Figure 17 Fuel usage throughout the year 33
Figure 18 Characteristic daily generation for winter 33
Figure 19 Characteristic daily monsoon season generation. 34
Figure 20 Solar generation 34

List of Tables

Table 1 Countries ranked by GDP 10
Table 2 Countries ranked by GDP per capita 10
Table 3 Comparison of available resources [57] 18
Table 4 Comparison table of energy and power storage technologies[58] 19
Table 5 Scale of Saaty 25
Table 6 Random consistency index 25
Table 7 Simulation parameters used in HOMER for each component 28
Table 8 Metrics used to evaluate criteria 29
Table 9 Results of preliminary simulations showing key parameters for each permutation 30
Table 10 Rankings of alternatives with respect to cost 31
Table 11 Rankings of alternatives for the reliability of supply 31
Table 12 Rankings of alternatives for GHG emissions 31
Table 13 Rankings ofor the risk of hardware theft 31
Table 14 Rankings of the difficulty in equipment transport 31
Table 15 The cumulative priorities for each criterion and alternative 32

1 Problem description

In many cases, the decision-making process for rural energy has neglected the factors that influence rural electrification because the majority of the proposals have not considered the needs of the population.[1] The installation of an energy system is inherently complicated with multiple stakeholders, many of whom may have conflicting opinions and requirements. It is possible to solve these complex problems by intuition, and this is often the case, however, this is unlikely to produce adequate results due to unforeseen consequences and conflicts. For this reason, it is important to use a multi-criteria approach which attempts to predict and mitigate these issues.[2–4]

Currently, 84% of the worlds unelectrified population lives in rural areas,[5] of which 40% live in South Asia.[6] The majority live in rural India, Bangladesh and Pakistan but Nepal offers an interesting case study since the earthquake of 2015 which demonstrates the need for robust and easily repaired electrification models. It is geographically and financially prohibitive to extend the current grid to remote regions, emphasizing the opportunity for decentralised generation. The national electricity grid, operated by the Nepal Energy Authority (NEA), experienced severe load-shedding of up to 16 hours a day.[7] Blackouts are still common practice in rural areas due to an ageing and over-subscribed grid network. This is despite an interconnection with India, allowing energy to be imported to meet peaks demands. The Himalaya mountains border the north of Nepal which makes the country heavily dependent on fuel imports from India, both in terms of grid imports and fossil fuels such a kerosene which a large proportion of the unelectrified population uses for heating and light.

The empirical results indicate that there exist long-run relationships between economic growth, energy consumption and carbon dioxide emissions for all countries.[8] It is therefore important to allow developing countries to grow in a similar way to Western countries. This must be balanced against the need to reduce global CO_2 emissions by 8-10% per year, according to the UN. Newly industrialising countries in the world require the space to develop and improve the welfare and well-being of their people. This means more cuts in energy use by the developed world.

When it comes to resource allocation the greatest improvement is seen by improving the weakest links in the system.[9] The argument is often made that money should be spent in larger cities where the most people will be affected but the finance required to noticeably increase the quality of life for these people is much higher than for those who have less to start with.[10] This decision should be made on a quantitative basis with a holistic approach to the problem, considering social, political, environmental and technical concerns.

1.1 Aim

The aim of this project was to determine the most suitable source of electrical generation for the town of Jiri in Nepal from a set of three alternative hybrid systems. Utilising demand-supply matching and multi-criteria decision methods, a comparison of electrification methods was made. The system was then simulated to ensure it would meet the energy requirements of the community.

1.2 Objectives

The objectives of this paper are as follows:

1. Propose and evaluate electrical generation models for the village of Jiri.
2. Determine the most favourable option by consulting with experts.

3. Ensure the selected system meets a set of operating criteria and can fulfil the requirements as the system evolves.

1.3 Outline of methods

A two-step approach was taken in the pursuit of providing electrical power to a rural community in Nepal. From the literature, a renewable-power mini-grid was determined to be the most appropriate approach since it is quicker and cheaper to implement than a grid extension and more reliable.[17,18] To determine the most appropriate renewable-based system is a complex process with more factors to consider than purely technical concerns.

The load requirements and possible generation methods were simulated with HOMER, an off-grid modelling tool. This tool facilitates detailed supply-demand matching and optimisation of economic factors. The selected system was modelled with every permutation of generation source and for the projected energy demand of the town of Jiri, assuming electrical energy usage follows the national mean.

To ensure the energy delivery models that were proposed meet the communities needs an analytic hierarchy process was adopted. The analytic hierarchy process (AHP)[19] allows all of these factors to be weighed and ranked by importance, this allows the most favourable alternative to be found. This project utilised AHP and surveyed 10 experts to reach a consensus regarding the most important factors. A high-level approach was taken, evaluating economic, social, environmental and technical issues. The most favourable solution was then examined in detail to ensure it met the current and future requirements of the system.

1.4 Structure

The structure of this dissertation is as follows:

Chapter 2 – Literature review

Chapter 2 presents a comprehensive literature review contextualising the state of Nepal's geography, economy and political system and giving some historical perspective. The literature review then examines the current energy mix, including the interconnection with India and the national grid expansion programme followed by the benefits and limitations of mini-grids. Forms of renewable generation and the potential national resource conclude the chapter, along with the barriers to renewable adoption and the theory of the analytic hierarchy process (AHP), a multi-criteria decision method.

Chapter 3 - Methods

This chapter presents the methods used during the project, detailing first the process and the assumptions made for AHP and then discussing the simulations conducted in HOMER. AHP is used to consider five criteria and three alternatives with the objective of finding the optimal electrical supply for the town in question.

Chapter 4 - Results

This chapter presents the most relevant findings of this investigation. First, the alternative systems are presented from preliminary simulations, followed by the results of the AHP survey and concluded with an in-depth look at the most favourable alternative and how well it meets the assessment criteria.

Chapter 5 - Discussion

Chapter 5 is a discussion of the results presented in the previous chapter.

Chapter 6 - Conclusions

The conclusions drawn from this project are presented in Chapter 6.

Chapter 7 - References

The final chapter provides a list of reference material consulted in the production of this dissertation.

2 Literature Review

2.1 National background

The current population is 29.9 million, according to UN estimates, with approximately 24 million living in rural locations. Whilst the national population of Nepal is projected to increase, the majority of this is expected in urban locations. The rural population is expected to remain relatively stable at between 24 and 25 million, for the period until 2045.[20]

The changes in land possession over time have led to complex affiliations, with some communities in the north associating themselves more with Tibetan culture than the Nepalese. These communities retreated to the mountainous regions to evade the rule of governments and so are detached from the political turmoil in Nepal, Tibet and China. This collection of non-state areas forms a region known, academically, as Zomia.[21,22] These isolated communities live a traditional lifestyle heading yaks and bartering for goods and services. This is beginning to change as an arterial road through Nepal to connect India and China is under construction, encouraging trading ties. With this comes a transition from a barter to a cash-based system.

2.2 Geography

Nepal is a mountainous, landlocked country in the Himalayas. It has a large variation in altitudes; from 64m in the south to 8848m in the north (Mt. Everest). It has three major river systems; the Kamali, the Gandaki and the Koshi.

Bon people, high in the Himalaya who do not have strong connections to either Nepali or Chinese governments and more closely connect to Tibetan culture. Retreated to this area specifically to avoid government interference and taxation, meaning they are unlikely to be interested in grid expansions etc. In addition to this, some of these groups are nomadic which obviously makes a conventional connection impractical.

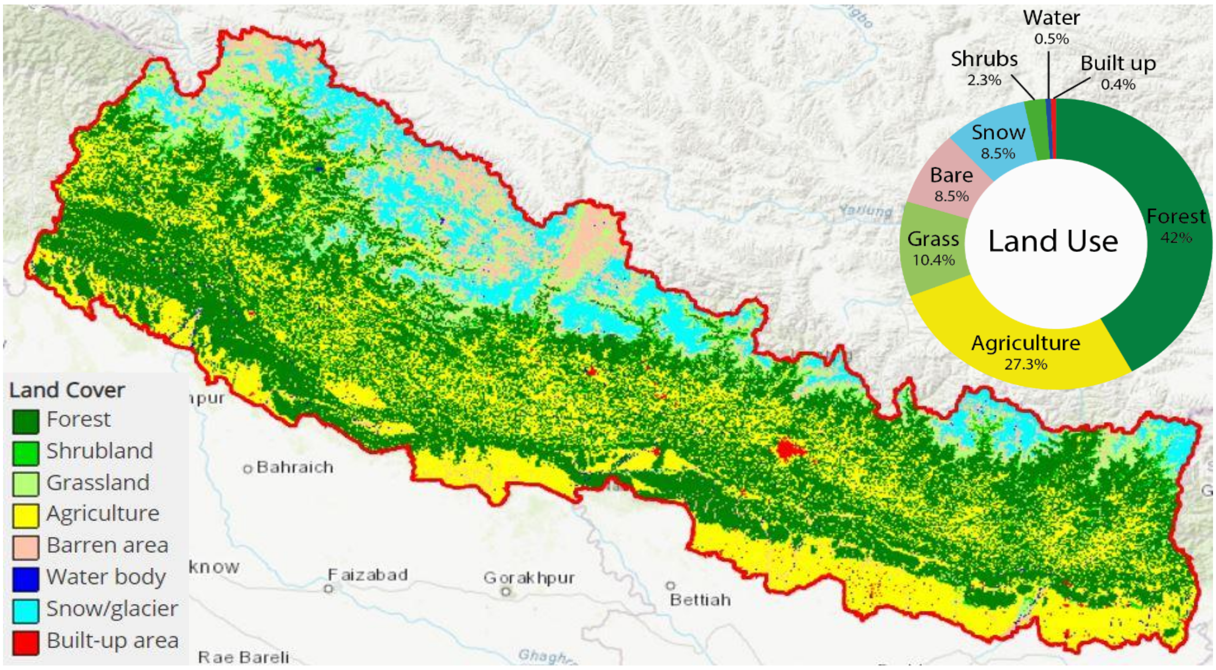

Figure 1 Land use map of Nepal [23]

2.2.1 Site selection

Jiri is located in the northeast of Nepal at an altitude of 1,900m above sea level. According to the 2001 census, Jiri has a population of 7,138 people living in 1,508 individual households. The township of Jiri was selected for this study for several reasons; it is located close to a motorway connection to the capital, it has an appropriate population, is on a hiking trail for Everest base camp and houses a meteorological station. The location of Jiri is shown in Figure 2.

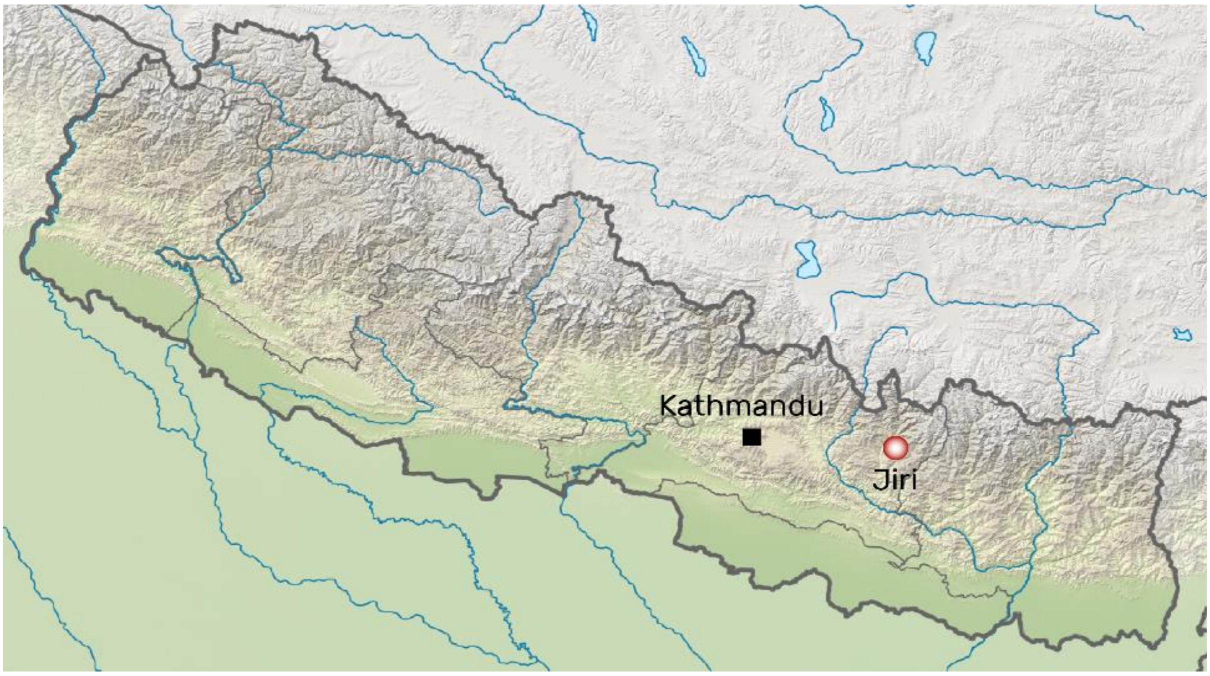

Figure 2 The settlement of Jiri, located 85km east of Kathmandu

Whilst the motorway is narrow and winding it is a superior road to many in the area and should allow comparative ease of transportation for any selected system. The villages location on a hiking route presents the potential for income-generating energy use by providing services to tourists as well as locals. The meteorological station at Jiri allows for temperature and precipitation data to be verified with the HOMER-generated profiles. In addition to these factors there is a large hydropower station under construction in the basin. The nearby Tamakoshi hydropower station will be the largest in Nepal, rated at 456MW (two-thirds of the country's current installed capacity). This means there will be an experienced workforce if run-of-river hydro is an appropriate solution for Jiri.

2.3 Political unrest

The Nepalese Civil War was a ten-year conflict fought between the government of Nepal and the Communist Party of Nepal (Maoist). The Maoist Revolution was launched on 13th February 1996 and come to an end with the signing of the Comprehensive Peace Accord on 21st November 2006.[24] The revolution was violent, resulting in the deaths of 17,000 insurgents, civilians, police and military personnel. The autocratic rule was overthrown, ending the 240-year reign of the Nepalese monarchy.

The civil war between the Maoist rebellion and the government of Nepal meant that political instability severely affected the state-owned sectors, including the energy sector, leading to fragmented leadership, changing priorities and policy discontinuity.[25] Between 100,000 and 150,000 were internally displaced, primarily from rural areas, this added to the disruption of rural development which affected the majority of projects.

2.4 Economy

The current expectation is that a country's economy should grow year on year. The standard measure for this is a country's gross domestic product (GDP) which is the sum market value of all the goods and services produced within its borders in one year. There are 211 states recognised by the International Monetary Fund (IMF) and Nepal's ranking is shown in Table 1 and several countries with similar GDPs.[26]

Rank	Country	GDP ($ Bn)	GDP per capita ($)
100	El Salvador	30.7	4,758
101	Uganda	29.7	671
102	Nepal	28.8	1,005
103	Papua New Guinea	27.4	3,123
104	Zambia	27.2	1,524

Table 1 Countries ranked by GDP

It is also important to consider the population of the country for an indicator of the standard of living. The GDP per capita is the GDP divided by the population which suggests how prosperous a country feels to its residents. As can see in Table 1 this value can vary significantly for similarly sized economies. Nepal ranks relatively well in the IMF rankings for its size in terms of GDP but when evaluated by GDP per capita it performs far worse, tabling at 183/211. This is shown in Table 2 where Nepal ranks countries whose economies that vary by almost two orders of magnitude.

Rank	Country	GDP ($ Bn)	GDP per capita ($)
181	Tanzania	61.6	1,063
182	Benin	12.2	1,034
183	Nepal	28.8	1,005
184	Mali	19.2	979
185	Comoros	0.8	918

Table 2 Countries ranked by GDP per capita

2.5 Current energy system

Due to the steep gradient and mountainous topography, Nepal is blessed with abundant hydro resources. The country's three major river systems and their smaller tributaries offer Nepal to produce economically and technically feasible nearly 50,000 MW power. Nepal can potentially generate over 90,000 MW hydropower. Despite having such huge hydropower potential, Nepal only generates around 847 MW from its hydro resources.

Today nearly half of Nepal's population have no access to grid-connected power. The shortage of power hinders the industrialisation and economic progress. Despite having huge hydro energy potential, only 1% of Nepal's energy requirements are fulfilled by hydropower. The energy mix of Nepal is dominated by fuelwood (68%), agricultural waste (15%), animal dung (8%) and imported fossil fuel (8%).[27]

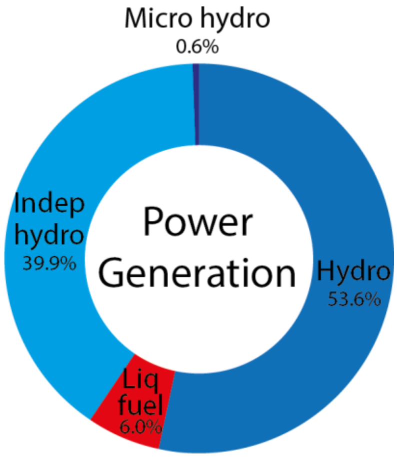

Figure 3 The current electrical generation in Nepal [27]

The large-scale hydro and liquid fuels shown in Figure 3 are state-owned, the independent hydro is privately owned by utilities and the micro-hydro is predominately community-owned.

The Nepalese government set targets to increase renewable generation in 2016. Principal amongst these was to generate 4,000 MW of hydroelectricity by 2020 and 12,000 MW by 2030 with an additional 50 MW of electricity from small and micro hydropower plants.[7] The government also stated its intention to equip every household in rural areas with smokeless, improved cooking stoves (ICS) by 2030.

Currently, most mini-grids are supplied by small-scale, run-of-river hydro systems due to the high number of appropriate sites and institutional knowledge. These systems are sized to meet peak demands for approximately 11 months of the year. The advantage of this is it leads to high peak-supply reliability, but the disadvantage is that a large amount of the power generated is dumped when it cannot be used. There are a relatively low number of communities that use solar or wind-based systems, which are decreasing in cost, but the government is actively investigating their feasibility.[28]

2.6 National electricity grid

2.6.1 Grid stability

As previously stated, Nepal has a significant hydropower potential but despite this, there is a shortage of electricity which results in scheduled power outages which last for extended periods. The country's current dependence on large centralised hydropower is especially obvious during the dry season, forcing the Nepalese Electricity Authority (NEA) to cut power up to 16 hours per day.[29] This grid instability is a significant barrier to growth since, as stated by Chen *et al.*, there is a long-established relationship between access to a secure energy supply and economic growth.[8]

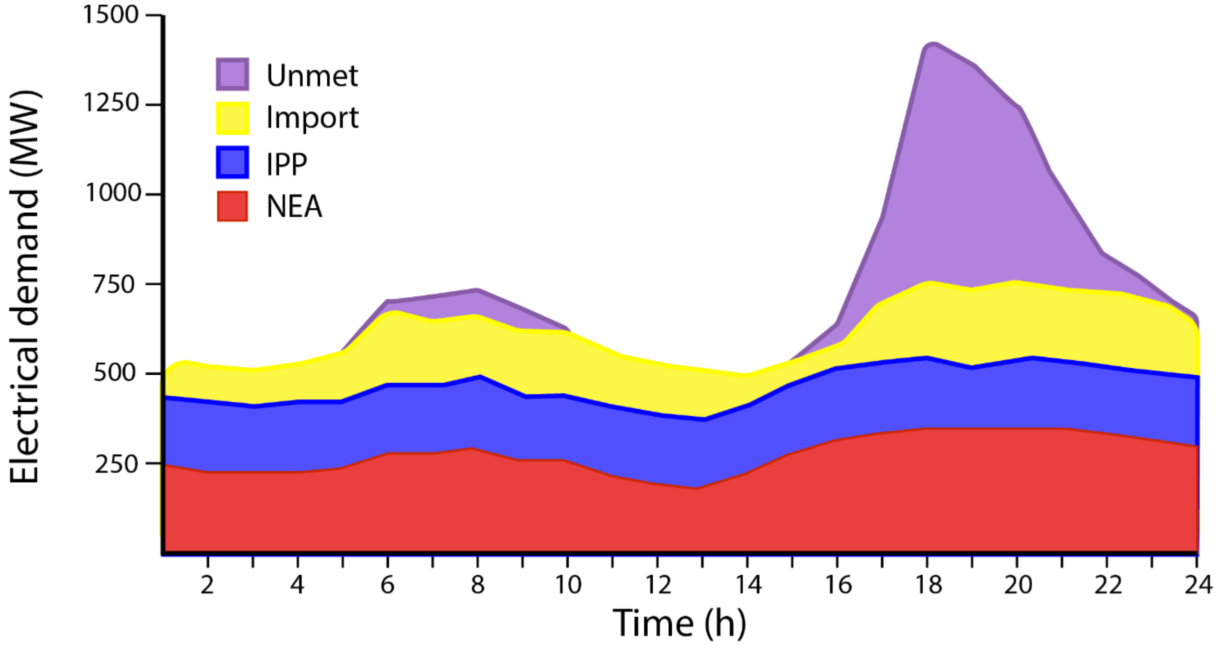

Figure 4 Nepal's electricity system load curve for 11th November 2015. The independent power producers (IPP) are presented in blue and the unmet demand resulted in load shedding. (Figure reproduced from NEA, 2016) [30]

In addition to this, energy theft is a major consideration. This is known as a non-technical loss (NTL) and has a strong negative effect on the grid. It is an issue across many developing countries[31–33] which increases grid instability and tariff prices to consumers. According to Yakubu *et al.*, energy theft is primarily a result of poverty and unemployment[33] and these factors are often more prevalent in rural and remote areas. The lower revenues due to energy theft limit the utilities capacity to maintain and improve the network, leading to higher tariffs. This in turn prices out lower-income consumers, leading to more energy thieves which perpetuates the issue. The financial implications are significant, with annual losses of $16.2bn and $10.5bn per year in India and Brazil respectively.

The nature of centralised generation means that transmission lines extend long distances and connecting isolated communities involves significant construction in remote areas. These remote areas tend to experience more extreme weather conditions, increasing the likelihood of damage to the lines. Locating and repairing a fault on these lines can be costly and time-consuming, especially when access can be difficult at best and almost impossible during the monsoon season. As a result of all of these factors, there are many villages where the grid system is in poor condition and characterised by either irregular flow or no flow of electricity for a large part of the day.[34]

2.6.2 Indian interconnection

The objective of the Nepal-India interconnection was to establish cross-border capacity between India and Nepal of about 1000 MW to facilitate electricity trade between the two countries and to increase the supply of electricity in Nepal by the sustainable import of at least 100 MW.[35] The project has not met these aims yet with a current operational capacity of 400MW. The benefits of the inter-connection have been observed in Nepal however, assisting NEA in ceasing brownouts. Winter peak loads and falling production from run-of-river schemes due to low water volume in rivers lead to Nepal meeting 58% of its electrical demand via imports on one day last winter, for example.[36]

The grid interconnection with India should reduce the investment requirement for Nepal and provide clean, renewable generation for India. This will also allow India to replace its fossil fuel-based generation with imports from Nepal.

2.6.3 Grid extension program

In an attempt to meet the rural electrification targets Nepal has undertaken a major grid extension program.[37] NEA has been successful in reaching more customers and, with the Indian interconnection agreement, in eliminating planned brownouts. However, despite the cessation of load-shedding practices many areas are still experiencing blackouts. The distribution systems and transmission lines are overloaded which has led to transformers exploding and feeders catching fire. Whilst this is an interruption to electrical services it is not technically called load-shedding. The environmental impacts of grid extensions can be significant too due to the inherently large scale of a nation-wide infrastructure. [4]

The net benefits of grid expansion programs have been conducted in the literature and multi-criteria decision methods suggest that this is not the most effective method of electrification, especially for rural and remote communities in developing countries.[38,39] The general consensus is that expanding the existing grid is likely to exacerbate the current issues and lead to a less reliable supply and greater load shedding. Therefore, centralised utilities should improve the service to existing customers before pursuing new customers.

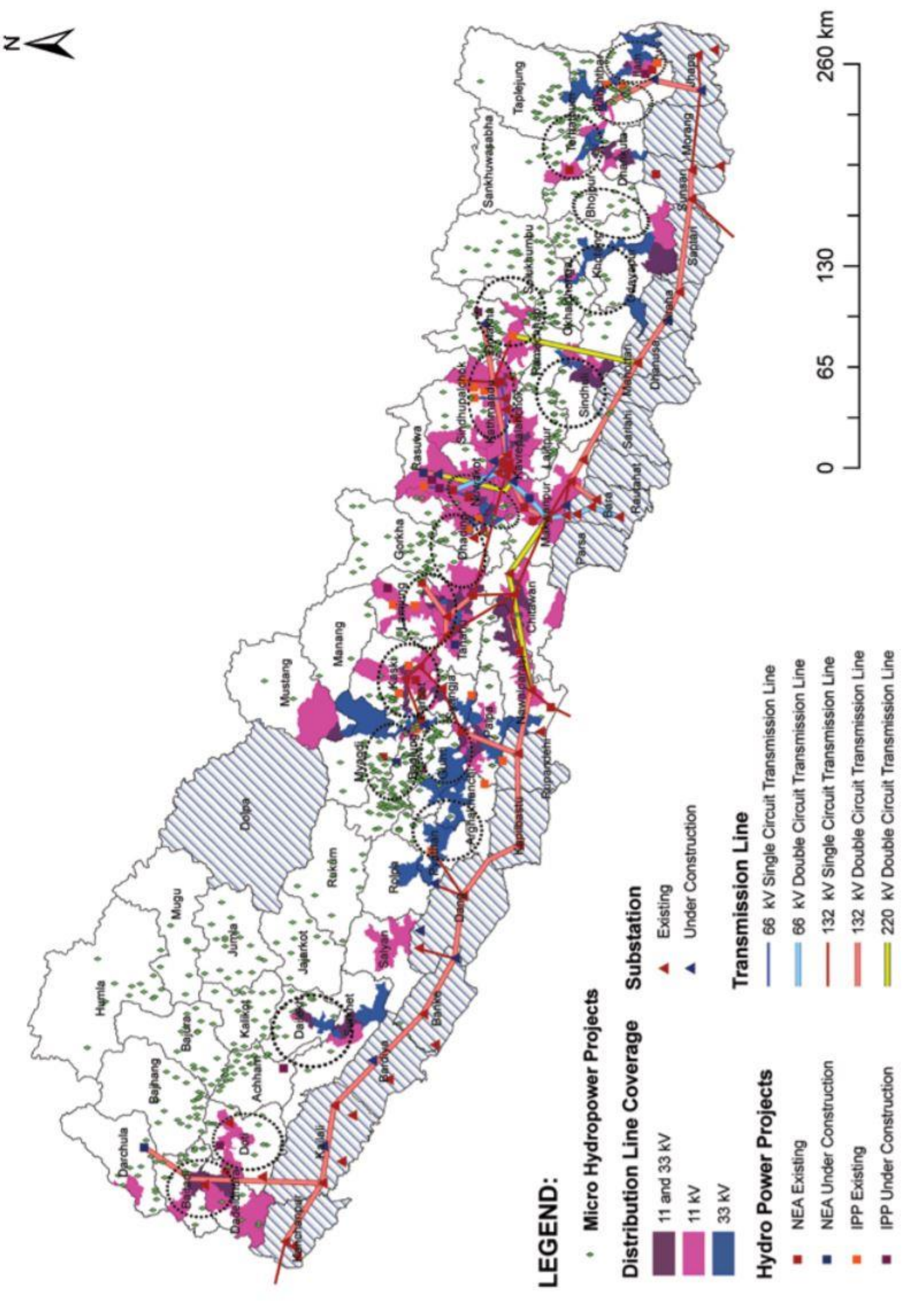

Figure 5 Map of national grid extensions[29]

2.7 Mini-grids

A mini-grid is an electricity generation and distribution network that supplies electricity to a localised group of customers. This may take the form of either tens or hundreds of consumers in a small remote village or thousands of customers in town or city. Mini-grids can be completely independent or have grid connections but with the capability to fully isolate the system.

Historically, mini-grids were the precursor to centralised generation. Small isolated systems evolved in parallel to the demand, technology and policies until the natural progression to interconnectors and standardisation. Early adoption took place in countries with robust socioeconomic systems, now considered developed countries. The development of the national grid in the United Kingdom is an example of this and the progression can be clearly seen by comparing distribution maps over time. This model was followed by emerging economies, but the implementation was not always so simple. For example, in Bolivia neighbouring mini-grids operated at different frequencies which led to complications in unifying the mini-grids into a centralised network.

The concept of centralised generation as the standard model for energy provision has led to the perception that mini-grids are inferior and a temporary solution until a grid connection can be established. This is no longer the case since a mini-grid can be a viable alternative to a standard grid connection. Sizing a mini-grid and optimising resource management is more complicated than for a national electricity grid since there are fewer redundancies in the system. To achieve this Boait *et al.* recommended that a mini-grid should comprise at least 50 households,[40] since this maximises the economies of scale and reduces the effect of demand variability.

2.7.1 Grid stability

The primary benefit of a mini-grid, with regards to stability, is that if it goes offline for any reason then it is only that grid and its users that suffer. In a conventional, large-scale grid an outage can affect a much larger population of downstream consumers. Energy theft is a key issue for national electrical grids in developing countries that is a lesser concern for mini-grids. Since many mini-grids are at least part-owned by the community they serve and this inclusion leads to a sense of ownership of the project, decreasing the likelihood of energy theft.[41] This, in turn, reduces the uncertainty in load and increasing the stability of the system. Precautions should be taken against energy theft though and any system should contain smart meters to ensure against energy theft.

2.7.2 Natural disasters

The Himalaya were formed by the collision of the Arabian and Eurasian tectonic plates 70 million years ago and the region remains seismically active today. The earthquake that hit Nepal in 2015 measured 7.8 M_W, killed nearly 9,000 people and injured nearly 22,000 more. The earthquake triggered avalanches and landslides, flattened entire villages and is estimated to require billions of dollars to rebuild. The region has experienced similar tremors before and, since the region is still seismically active, it is important that any infrastructure takes account of this and is designed to withstand future earthquakes. From an energy perspective, it was observed that in the aftermath of the earthquake much of the population reverted from modern fuels to fuelwood and kerosene to ensure energy security.

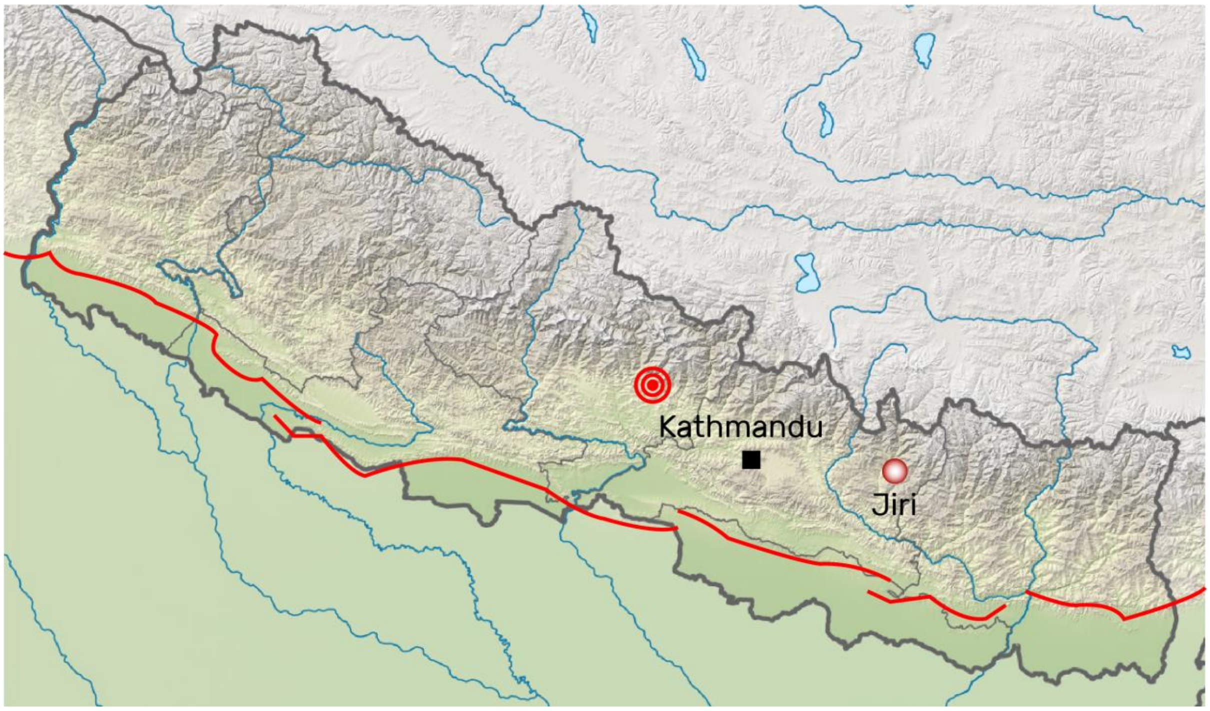

Figure 6 Map of Nepal showing fault lines in red and the 2015 earthquake epicentre north west of Kathmandu

The generation technologies must also withstand the atypical loads caused by earthquakes. These loads are a combination of seismic and wind loading,[42] the horizontal axis turbines that have become the industry standard are designed for low-speed, low-variability winds in flat, wide-open areas and designed to IEC 61400.[43] There is little in the literature regarding their response under such loading.

2.7.3 Cybersecurity

Storms and natural disasters are not the only threats to electrical grids, the increasingly connected nature of infrastructure poses cybersecurity risks too.[44,45] Tens of millions of people in Argentina and Uruguay were left without power when the central line supplying these countries failed in spring 2019.[46,47] Initial reports suggested it may have been due to a cyberattack, further investigation has shown that this was not the case but this does demonstrate that it is perceived as a credible risk and moreover shows the vulnerability of a large grid. The United States claims to have launched attacks on Russia's grid by implanting malware.[48] Isolated systems are less of a threat and protect the rest of the system since they do not have the same tactical impact that a large grid does.[49]

2.8 Renewable energy technologies

Renewable generation technologies utilise sources of energy which replenish at the rate they are consumed and as such are not finite, unlike fossil fuels. Renewable technologies have an initial CO_2 cost in their construction and installation but little to no CO_2 emissions in the generation process.

2.8.1 Hydroelectric

Hydropower converts the kinetic energy of water into electrical energy by turning a turbine. The two primary forms of hydro are dammed (creating a reservoir) and run-of-river. The principal advantage of conventional reservoir hydro is the dispatchable nature of generation since water can be stored high above the turbine and released as needed. This allows power to be generated flexibly to meet demand, typically adjusting to changes in demand within seconds. Hydropower can be classified by generation capacity, as defined by the Department of Energy: large-scale hydro (over 30 MW), mini-hydro (between 1 and 10 MW) and micro-hydro (less than 100 kW).[50]

The potential hydro resource in Nepal is approximately 83GW, of which 43GW is technically and economically possible.[39] This is power extraction is based in large-scale hydro projects, the untapped potential of mini and micro-hydro schemes is in excess of 100MW. These smaller systems were developed for smaller communities and so are well suited for decentralised generation, particularly for mini-grids.

2.8.2 Wind

Wind turbines convert kinetic wind energy into electrical energy by turning rotor blades which in turn spin a turbine. Many variations of this technology exist, the most common for large-scale generation is a horizontal-axis configuration with a large supporting tower, a nacelle with houses the generator and a drive shaft which connects the generator and three blades that rotate around this axis.

The theoretical potential is around 3,000MW but Nepal has not achieved significant progress in wind energy installation.[51] The government of Nepal is attempting to correct this and is collecting data for a feasibility study and amendments to policy have been made to support this. The available national resource is shown in Figure 7.

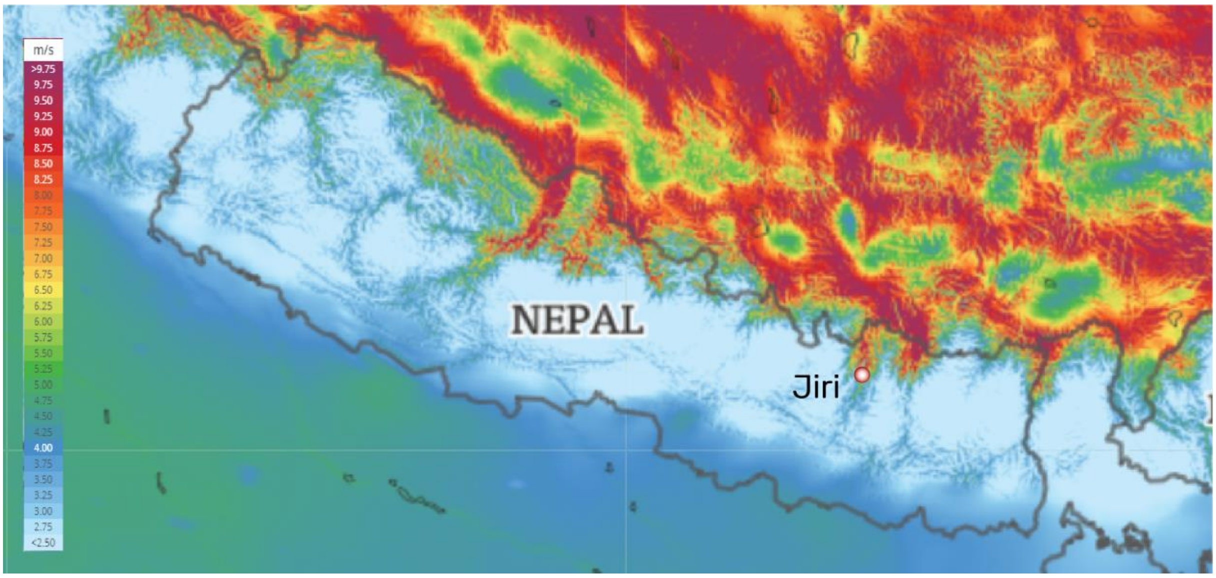

Figure 7 Wind speed data for Nepal [52]

2.8.3 Solar

Solar photovoltaics (PV) convert sunlight into electricity by utilising the photoelectric effect. A single solar panel can provide electricity for a household or combined in an array to increase installed capacity. Concentrated solar uses a series of lenses or reflecting mirrors to focus the suns energy to a small area, creating temperatures high enough to melt salts and create steam in a secondary system which turns a turbine to generate electricity. This configuration requires vast areas of flat land and so it not suitable for mountainous regions.

Mainali *et al.* argued that solar PV technology was not within the reach of the economic poor[53] and this was supported by Ghimire *et al.* since access to credit and poor policy implementation have been impediments to uptake.[39] These universal barriers create an opportunity for energy entrepreneurship, encouraging novel delivery methods.[54] For example, in Kenya and Tanzania, there has been a steep increase in the number of small home solar systems. The solar PV system is sold bundled with a light, a radio and electrical storage to encourage energy usage.

Nepal has an energy production intensity of 3-5 KWh/m^2 solar energy and the country's economically feasible grid-connected potential is 2100MW and the off-grid potential may be higher still. The small solar home system is becoming an affordable solution for rural areas with around 600,000 solar systems installed in rural areas of Nepal.

2.8.4 Bio-energy

Nepal has a high population of cows, buffalo and yaks, particularly in rural areas. This livestock produces a large amount of dung that can be treated to produce “gobar gas”, a form of biogas.[55] The methane gas generated in the process can be combusted and used in a thermal power plant or, at a smaller scale, can be utilised for cooking. Based on an assessment report published by the Nepal government, around 1 million households in the country are able to produce energy from biogas plants.[39]

The principal source of energy consumed in Nepal is solid biomass in the form of fuelwood, which accounts for 68% of energy consumption, primarily used for cooking and heating. This is shown in Figure 8.

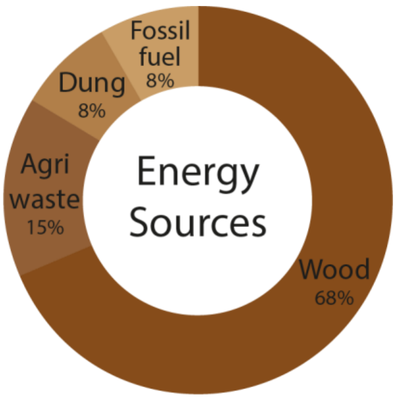

Figure 8 Current sources of non-renewable energy[39]

According Bhattarai *et al.* 62% of households surveyed in Nepal own at least one cow or buffalo.[56] Burning biogas produced from manure has the benefit of eliminating methane, which has a more potent GHG effect, and producing CO_2 in its place.

2.8.5 Generation potential

A comparison of the potential renewable resources is presented in Table 3 below. It is important to note that the peak demand is 1,200MW.

Table 3 Comparison of available resources [57]

Generation source	Available potential (MW)
Solar	2 100
Wind	3 000
Hydropower	43 (Economical) 83 000 (Technical)

2.8.6 Storage

The principal limitation of renewable energy technologies in the current infrastructure is the stochastic nature of the generation. With the exception of reservoir hydro, there are no intrinsically-dispatchable generation technologies. Consequently, any fluctuations in demand experienced by the grid can cause instabilities. Conventional gas and coal-fired power stations contain a large turbine which, when turned by steam power, drives a shaft which produces electricity in a generator. The large rotating mass of the turbine can temporarily be exploited to meet spikes in demand by extracting some of this kinetic energy.

In addition to the previously mentioned pumped hydro storage (PHS) current energy storage technologies include mechanical methods such as compressed air energy storage (CAES) and flywheel energy storage (FES).

Electrical energy can also be stored with chemical methods in batteries. The specific properties of each form of battery depend on the chemical components and include lead-acid, nickel-based (NiCd, NiMH and NiZn), sodium-sulphur (NaS) and flow battery energy storage (FBES). Capacitors, supercapacitors and superconducting magnetic energy storage (SMES). For response times: good is classified as less than one second, fast is defined by the millisecond range and very fast is less than milliseconds.

Table 4 Comparison table of energy and power storage technologies[58]

Technology	Efficiency (%)	Capacity (MW)	Energy density (Wh/kg)	Capital ($/kW)	Capital ($/kWh)	Response time	Lifetime (years)	Maturity	Environ. impact
CAES	50-89	3-400	30-60	400-2000	2-100	Fast	20-60	Developed	Negative
Flywheel	93-95	0.25	10-30	350	5000	Very fast	~15	Demo	Almost
Pb-acid battery	70-90	0-40	30-50	300	400	Fast	5-15	Mature	Negative
Ni-Cd battery	60-65	0-40	50-75	500-1500	800-1500	Fast	10-20	Commercial	Negative
Na-S battery	80-90	0.05-8	150-240	1000-3000	300-500	Fast	10-15	Commercial	Negative
Li-ion battery	85-90	0.1	75-200	4000	2500	Fast	5-15	Demo	Negative
Hydrogen	20-50	0-50	800-10,000	500-1500	10-20	Good	5-15	Developing	Small
Flow battery	75-85	0.3-15	10-50	600-1500	15-1000	Very fast	5-15	Developing	Negative
Capacitor	60-65	0.05	0.05-5	400	1000	Very fast	~5	Developed	Small
Supercapacitor	90-95	0.3	2.5-16	300	2000	Very fast	20+	Developed	Small
SMES	95-98	0.1-10	0.5-10	300	10,000	Very fast	20+	Demo	Benign

2.9 Barriers to renewable energy uptake

Despite the significant resources outlined in 2.8, there has been a limited adoption rate, with the principal share being large-scale hydropower. Ghimire *et al.* outlined the barriers to renewable energy uptake and grouped them into six categories, namely: social, political and policy, technical, economic, administrative, geographic barriers.[39] These were determined from a literature review, site visits and interactions with stakeholders (such as suppliers, installers, manufacturers, consumers and experts) as outlined by Painuly.[59] Each of these is summarised in turn below.

2.9.1 Social barriers

Various social barriers to the adoption of renewable technologies exist. Despite the environmental and increasing financial benefits of renewable technologies, the lack of access to this information has limited the social awareness and motivation to change generation source. Renewable generation is usually proposed for off-grid or mini-grid applications in rural and remote locales where the mean income is generally lower, this results in a lack of consumer paying capacity.[60] There is also a lack of social acceptance since Nepal is a conservative country with a preference for traditional technologies. To overcome this social inertia, acceptance is required from local stakeholders, communities and local authorities.[61]

2.9.2 Political and policy barriers

The political climate, particularly political stability, plays a crucial role in the successful adoption of renewable technologies.[62] Nepal has experienced significant political instability, as previously stated. The long-term internal conflicts have resulted in frequent change and a lack of continuity. The instability also moves the governments focus away from energy policy as the threat to their control is more pressing. This, in turn, means that policies are implemented sporadically to facilitate the growth of specific technologies, rather than a more considered, strategic approach. There is also a lack of transparency with a failure to hold regular consultations in the decision making process.[59] The increase in uncertainty in the country can also dissuade foreign investment due to the risk to their assets.[63] As with many developing countries, corruption and nepotism are prevalent in Nepal, with some estimates stating that 2% of the economy in Nepal is "formal", meaning the bulk of activity is untaxed and unregulated.[64] Sovacool *et al.* continue that energy projects only progress after a successful bribe. This misuse of public funds leads to delays and an unwillingness of groups to negotiate with the state.[39]

The technical barriers are widely acknowledged in the literature and have been the primary focus of engineers. Due to limited research and development facilities and sufficient economic backing, the technical advancement of renewable generation is hindered in developing countries. Therefore, countries like Nepal rely on technological information transfer and spillover.[65] Reliance on technology from more affluent countries poses the concern that the solution is not tailored to the specific site and requirements. For example, horizontal axis wind turbines were developed to operate in flat, open environments like the southern United States, Denmark and offshore. These operating conditions do not exist in the upland regions of Nepal which would encourage the utilisation of poorly adapted technology, rather than developing tailored solutions. The reliability of the system is also a noted concern. Most renewable generation is stochastic in the short-term (e.g. wind),[66] varies with daily cycles (e.g. solar) and experiences seasonal periods (e.g. run-of-river hydro). Nepal's hydro installations are sized to maximise generation during the rainy season. The lack of water during the dry season leads to brownouts and blackouts due to insufficient generation. The risk to the supply of a mini-grid resulting from maintenance to either the distribution or generation equipment is a concern for the private sector. Since these technologies are often in rural and remote areas access for routine, planned maintenance and repair is restricted and increases the likelihood of unscheduled outages that last longer due to more serious damage. The lack of an inherent grid connection limits the export potential of renewable generation since they cannot sell to the national electricity grid.

2.9.3 Economic barriers

Economic factors are a considerable barrier to the adoption of renewable technologies in developing countries, principal among these are the high capital costs and a lack of access to finance. Since renewable technologies are not as developed or mature as conventional generation methods the associated costs have not reached the same low levels. Although the cost of renewable technology has fallen over recent years, particularly for solar, [49,56] they are not yet at a widely accessible price-point. The state of subsidies, incentives and financing opportunities will be outlined here and examined in greater detail in section 2.11. Due to the high costs in relation to the available capital government interaction is required to stimulate change. This can be achieved through subsidies, tax exemptions, low-interest loans and long-term credit.[51] There is a high demand for this in developing countries, however, the subsidy policy must be supported with sufficient funding and that has not always been the case in Nepal.[39] Governmental subsidies only provide partial funding and local stakeholders have limited finances, therefore partial credit is required from a non-governmental organisation such as the World Bank to facilitate construction.[62,67] The insufficient market demand is also a barrier to the conversion to renewable electricity generation since the economies of scale cannot be exploited, which hinders the reduction in price which is vital to encourage private investment.[68] The current energy demands follows a general pattern with peaks in the morning and evening with low demand during the day. This requires a higher capacity system to accommodate these peaks. If the demand during the day was increased, however, this would reduce the required maximum capacity and reduce the overall investment required.[34,69]

2.9.4 Administrative barriers

Once policies have been passed by the government they must then be implemented. In addition to the previously mentioned funding implications, there are several administrative factors that hinder this process. Renewable technologies differ greatly from the existing energy systems and therefore require a different skillset to install and maintain. There is a lack of these skilled workers in countries with low renewable penetration and the workforce is often not supported by the government to retain.[41,70] When departments and organisations work in isolation the probability of work being repeated increases, this is inefficient and increases the cost and overall project timescale. A central administration system is key in minimising these inefficiencies and encouraging coordination between institutions.[39] This lack of coordination increases the workload of each contributor and reducing the capacity of each institution to complete the project on time and under budget. Each body has finite resources and inefficient use of these could dissuade the development of renewable energy. The complexity in the application process for funding and subsidy approval also limits the number of applicants, thereby decreasing the total number of renewable projects undertaken.

2.9.5 Geographic barriers

The complex topography of Nepal creates two principal geographic barriers to the development of renewable energy: transportation and widely distributed housing. Renewable technologies are often deployed in remote areas with poor road conditions. This drives up project costs and completion times.[57] These remote locations, by definition, have low population density, making it costly and complicated to implement transmission and distribution networks.

2.10 Effects of climate change

It is important to consider the wider picture and be aware of how the environment is likely to change over the lifespan of any system considered. The Intergovernmental Panel on Climate Change (IPCC) predicts continued global temperature rise, changes in precipitation patterns, more droughts and heatwaves, more severe and frequent storms, sea-level rise and melting ice caps.[71] Obviously, not all of these will directly affect Nepal, for example, the country is landlocked so rising sea levels will not impact the country explicitly. [72] However, the increase in frequency, severity and duration of storms, in addition to the melting of glaciers due to global temperature rises will.

The melting of upland glaciers presents a potential future problem in terms of fresh water. Locals rely on the glacial meltwater as a source of drinking water, for cleaning purposes and for energy production in the form of run-of-river hydro schemes. The meltwater contribution of glaciers is particularly important for hydropower projects during dry seasons.[73] Temperature trends are important for the fate of glaciers and, whilst these are predicted to rise, there is potential to examine this as an opportunity instead of purely a negative outcome. Greenland has replaced conventional diesel-powered plants with meltwater hydropower. It is important to note the sediment transported by glacial meltwater is particularly abrasive though and this must be considered in the proposal of any run-of-river project.

The predicted increase in frequency, severity and duration of adverse weather events is likely to decrease the lifespan of existing turbine designs and require more maintenance. Turbulence is a determining factor in hardware life expectancy since increases in the variation of wind speeds increases the mechanical stresses in the system. This, in turn, increases the operating and maintenance costs which may make this form of generation less financially attractive.

2.11 Finance

The development of renewable energy requires abundant financial support both from banks, governments and private investment.[74] As the economist CK Prahalad outlined in 2002, it is the billions of aspiring poor who are joining the market economy for the first time that is the real market promise.[75] He advocated for inclusive capitalism that would support billions out of poverty. "Companies will be forced to transform their understanding of scale, from a "bigger is better" ideal to ideal of highly distributed small-scale operations married to world-scale capabilities. … producing and distributing products and services in culturally sensitive, environmentally sustainable, and economically profitable ways." This approach of companies and institutions working in partnership with communities is becoming more common with many mini-grids are at least partially owned by the communities they serve, often run by a village committee which handles the operation of the system. The committee also centralises the financial aspect of the scheme which has the advantage of minimising payment defaults.

Typically rural and remote populations have low, unstable income, few savings and a lack of experience in purchasing durable goods[76] which simultaneously increases their need for credit and decreases their likelihood of being accepted for it.[77] The access to this credit is generally not available from conventional sources of requires assurances in the form of either a regular income or collateral which poor people often do not possess.[54,76,78] For example, in Kenya companies are financing off-grid solar systems paid in small daily instalments by mobile phone-based money transfer services and has seen the access to rural electrification rise from 20% to 65% in four years.[5] In Malawi however, the electricity company demands a full upfront payment of the 30-year cost of line extension, resulting in a renewable energy rate of only 2%.[79] Demanding this large upfront investment and the lack of credit is a major barrier renewable technology adoption and entrpreneurship.[80–83]

Hartvigsson *et al.* also suggest that the combination of the size, timing and period of repayments is important. Since the daily income is low then lower repayments over a longer period are preferential to higher instalments over a shorter period. This decreases the short-term burden on consumers and encourages them to accept this debt. It is important that this is adapted to specific market requirements. In Zimbabwe, payment plans have been adjusted to reflect consumer cashflow. Instead of monthly payments, a single, large payment is made once per year following the annual cotton sale, when funds are available.[84]

2.11.1 Subsidies and incentives

From a growth perspective, it is important that companies can undertake a certain level of risk and debt. Nie *et al.* found that government subsidies raise outputs and debt levels of renewable energy firms and improve shareholder value.[74] Their microeconomic approach considered all stakeholders including the government, banks and shareholders of the firm.

Despite the recent turbulent governmental situation, Nepal has enacted a series of measures to support the development of clean energy sources. The government has placed a particular focus on off-grid systems which should encourage a timely transition to renewable generation. Typically an off-grid system will receive around 40% of the project cost covered by this subsidy, 30% from the community and 30% from loans and commercial financing, but far higher subsidies are available under certain circumstances.[85]

Nepal has provided subsidies to remote and rural communities since the 1970s to promote the use of biogas technologies and the 1990s in the form of the solar home system (SHS) subsidy policy. The SHS subsidy policy has been more effective at reaching poor households than the biogas subsidy. [56]

This is a degree of criticism regarding this policy though, close analysis of the applications shows that whilst the support is going to deprived, off-grid areas it is the richer households within those areas which are capitalising on the opportunity. This shows that the scheme is not working as intended since the consumers that require the most assistance are not receiving the help they need. The approach taken in Kenya was to remove the value-added tax on solar imports which contributed to a threefold increase in electrical access.[5]

Microfinance is a form of financial service aimed at individuals and small organisations who cannot access conventional banking services. Microcredit, a subset of microfinance, provides loans to poor clients of sums that, to developed countries may seem small but can have a large impact in these scenarios. Microcredit is playing a vital role in the proliferation of renewable energy technologies in developing countries when loans are carefully structured to suit the local conditions.[86]

Microcredit can be deployed to finance the purchase of RETs or, as is increasingly common, household appliances. In poor communities that are unelectrified, there are no electrical appliances to connect once an electrical supply has been secured. It is important to maximise the benefit from an electrical supply and use appliances such as refrigerators. Encouraging individuals to increase their power demand is counterintuitive with regards to the global approach to energy, where an overall reduction of energy consumption is preferable, however, it makes sense in this scenario. Older appliances are less energy efficient so whilst they are cheaper to buy initially, they are more expensive to operate and require more costly repairs than a newer alternative, increasing the overall cost of the product. Bhattacharyya *et al.* suggest that the acquisition of appliances should be a focus of subsidies to encourage revenue-generating purchases.[17]

Blockchain is an emerging trend in energy financing which removes the hierarchical structure and need to trust the central figure.[87,88] Blockchain works by decentralising the ledger of transactions and redistributing it to every user. When a transaction, or block, is made the details are checked with every user in the network and is completed when more than half of the users confirm the transaction is valid, based on the available funds. The whole system is encrypted, and each transaction follows on from the previous one, with randomised but repeatable links to create a chain. The system is secure since the encryption cannot be cracked by a brute force attack due to the phenomenal computing power required and the chain is secure since an edited block cannot be confirmed unless the user-controlled more than half of the network. Combining a decentralised financial system as well as generation system is an active area of research and has the potential for safe and secure energy development in a post-trust era.[89,90]

2.12 Multi-criteria decision methods

Multi-criteria decision making (MCDM) techniques allow complex problems with multiple, often competing and conflicting, factors to be resolved by numerical methods. It is possible to provide a solution to these problems by intuition, and this is often the case, however, this is unlikely to produce adequate results due to unforeseen consequences and conflicts that arise. For this reason various MCDM techniques have been developed to aid in decision-making processes for many applications, including renewable energy planning and development.[38,91,92]

Many different forms of MCDM techniques have been developed including; analytic hierarchy process (AHP), preference ranking organization method for enrichment evaluation (PROMETHEE), elimination and choice translating reality (ELECTRE), technique for order preference by similarity to ideal solutions (TOPSIS) and multi-attribute utility theory (MAUT). AHP has also been adapted for different applications, by use in combination with VIKOR for example.[4,93,94] However, the process is still robust and is simple enough for use in isolation with explorative assessments such as this project.

2.12.1 Analytic Hierarchy Process

The AHP was proposed by Saaty[19,95] and is a method which allows the decomposition of complex problems into a more understandable hierarchical model. The AHP approach has been used to solve a wide variety of problems, including: selecting industrial robots for milling applications,[96] selecting hazardous waste containers,[97] determining the best 3D scanner for cultural heritage applications,[98] choosing catering suppliers and the transport of oversized cargo through a city,[99] in addition to evaluating university web pages[93] and Internet of Things (IoT) enterprises.[100]

The method allows the decision-maker to construct a hierarchical model which consists of three levels; the goal, the criteria and alternatives. Pair-wise comparison is then conducted between criteria and alternatives. Numerical values are attributed to the preferences indicated by surveyed experts and then aggregated to create a combined preference. Once these paired preferences have been entered into a matrix of paired comparison the problem then reduces to the calculation of eigenvalues and eigenvectors, which represent the priorities and the consistency index of the process, respectively.[4] For consistency, A is only consistent if Equation 1 is satisfied:

$$A * w = \lambda * w \qquad \text{Equation 1}$$

where A is the reciprocal matrix of paired comparisons (preference judgments of one criterion over another), λ is the maximum eigenvalue, A and w is the eigenvector corresponding to λ. To calculate the consistency ratio (CR) of preferences for each decision-maker, Equation 2 is used:

$$CR = \frac{CI}{RCI} \qquad \text{Equation 2}$$

where *CI* is the consistency index of *A* and *RCI* is the random consistency index, found in Table 6.

The consistency index of *A* is determined by Equation 3:

$$CI = \frac{(\lambda_{max} - n)}{n - 1} \qquad \text{Equation 3}$$

where *n* is the number of elements that are compared (criteria) and λ_{max} is the maximum eigenvalue.

For a consistency ratio lower than 0.1 the result is deemed acceptable and the solution is considered consistent. For a CR > 0.1 the result is inconsistent, and the respondent must repeat the process until a satisfactorily consistent value has been achieved.

Since the role of AHP is to determine the best solution to a complex given problem, this requires the input of experts in variety of fields. The number of respondents required to generate an acceptable outcome is widely contested in the literature, Saaty suggests the process could be completed by a single respondent (in the case of purchasing a house, for example) whereas Singh *et al.* argued that at least 70 are required for reliability.[101]

Table 5 Scale of Saaty

Value	Definition	Comment
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one activity (criterion A) over another (criterion B)
5	Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The increasing importance of the criterion A over B is irrefutable
2, 4, 6, 8	Intermediate values	
1/3, ¼, 1/5	Reciprocals	The reciprocal of each value above is possible to show a equal but opposite favour

Table 6 Random consistency index

(n)	1	2	3	4	5	6	7	8	9	10
(RCI)	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

3 Methods

The approach taken by this investigation was to model three alternative electrification technologies commonly utilised for renewable mini-grids and then evaluate their suitability in a more holistic manner with the analytic hierarchy process.

3.1 Simulations

3.1.1 Modelling tool selection

HOMER[102] is a community-scale tool, originally developed to support design of off-grid community scale electrical energy systems.[103] The software can model a variety of generation and storage options and optimises for financial outcomes.

3.1.2 Demand profile

The construction of mini-grids requires a detailed electrical demand profile, often on an hourly basis, to accurately size the system. There is currently little measured data on the electrical demands of rural mini-grids and the most common method of estimation is based on interviews regarding appliance usage.[69] However, this has proved to be inaccurate and often underestimates the actual demand. The lower estimates can make mini-grids appear less financially attractive than they actually are.[69] The National Energy Strategy 2010 predicts the annual electrical power consumption will be 234 kWh per capita next year in Nepal. Rural areas have a lower electrification and therefore electricity usage so it is assumed that the population will meet this national mean. This results in a daily consumption of 4.58MWh for Jiri. Based on these values a demand profile was generated in HOMER Pro using the community profile shape, this combines commercial and residential profiles with a degree of variability to generate a single profile. Characteristic days from each month are shown in Figure 9. This was found to be in agreement with the work of Sharma *et al.*[104] The profile was constructed with hourly timesteps, a peak in July (as shown in the literature), day-to-day variability of 10% and timestep variability of 20%.

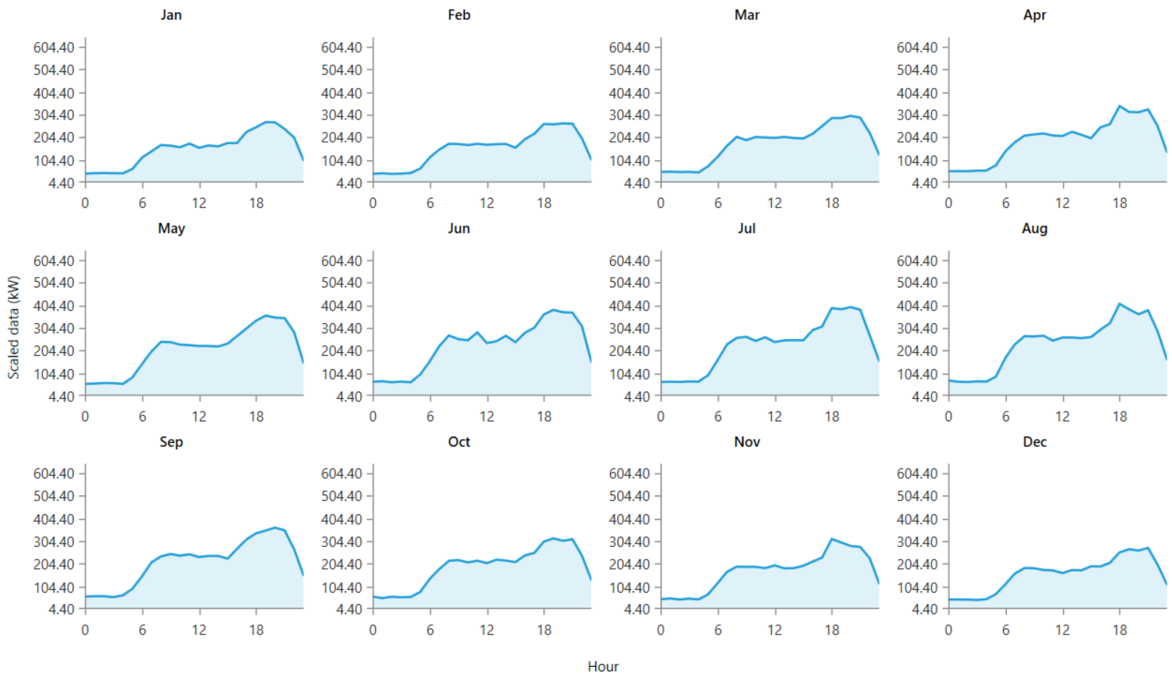

Figure 9 Characteristic daily demand profiles for month

3.1.3 Resource prediction

Solar radiation data was obtained in HOMER for the location 27°38'N 86°14'E from the NASA surface meteorology and Solar Energy Database.[52] This publicly available dataset consists of 22 years of monthly averaged data, in the form of gridded global solar and meteorological data. The HOMER-generated solar profile is shown in Figure 10.

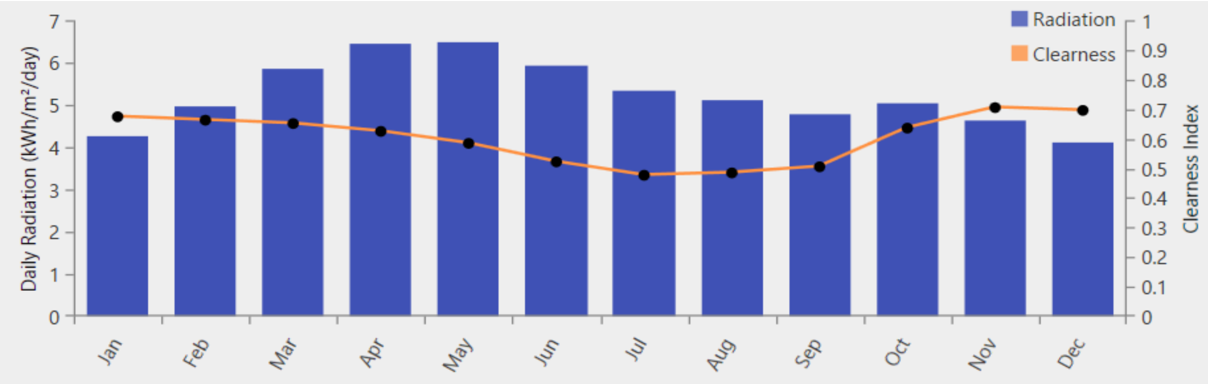

Figure 10 Solar radiation profile

To accurately model the available resource, it is important to consider daily, seasonal and annual variations. According to meteorologists five years of data is required for reliable average annual wind speeds and 30 years of data for long-term average wind speeds.[66] One year of data can provide average seasonal wind speed with an accuracy of 10% at a confidence level of 90%.[105] The NASA dataset provides this and the generated wind resource is shown in Figure 11.

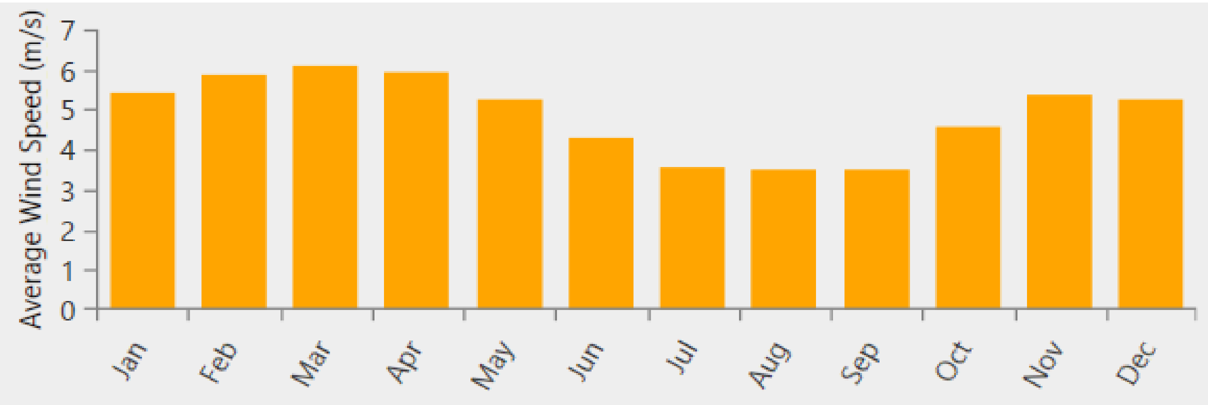

Figure 11 Wind resource profile

For biogas it is assumed that the average cow in Nepal produces 10kg of manure per day. It is also assumed that the population of Jiri its comparable to that surveyed by Bhattarai *et al.* [56] with respect to livestock ownership, this would results in approximately 44,300kg of dung per day. This supply would convert to roughly 1,100m^3 of biogas per day. It is assumed that variation in diet, which varies seasonally, has no notable effect on the production of dung.

The hydro resource is the product of both precipitation and glacial meltwater.[106] Precipitation in upland basins is not always released directly into the river system, a large proportion is held in glaciers over the winter and released when temperatures rise over the summer.[107] Therefore, the hydro resource varies seasonally, with high river levels during the monsoon season and lower levels during the winter. The Tamakoshi river provides ample resource with an annual average flow of 68.03m^3/s.[108] The mean stream flow for each month is shown in Figure 12.

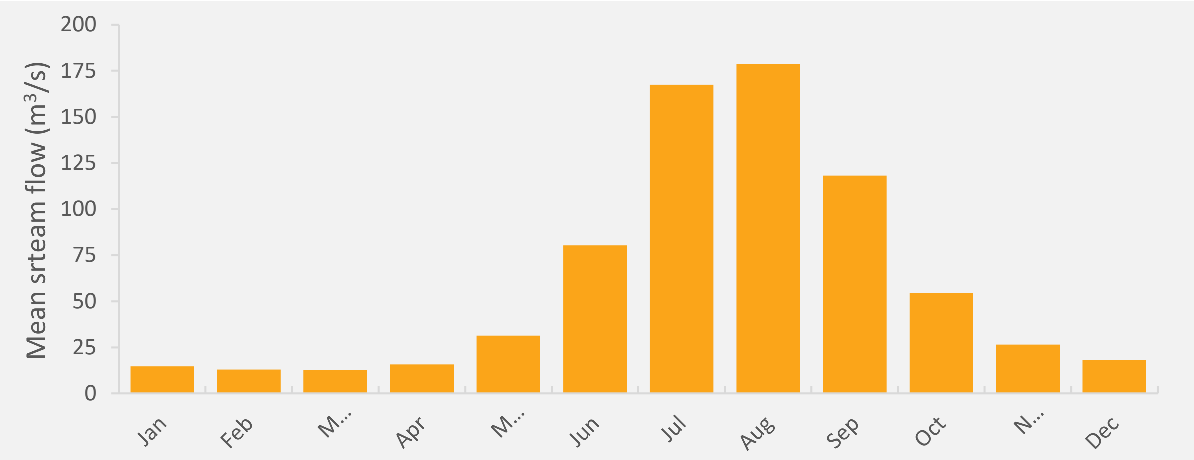

Figure 12 Mean stream flow of Tamakoshi river [108]

3.1.4 System design

The system was structured as shown in the schematic below (Figure 13). The schematic shows a biomass generator, a hydro generator and a wind turbine on the AC side of the system and PV generation and Li-ion batteries on the DC side. These are controlled through a converter to allow distribution to the AC load. The generic forms of each piece of hardware (generated by HOMER) were used in each case and scaled with HOMER financial optimisation. Each hardware permutation contained a battery to facilitate dispatchable power.

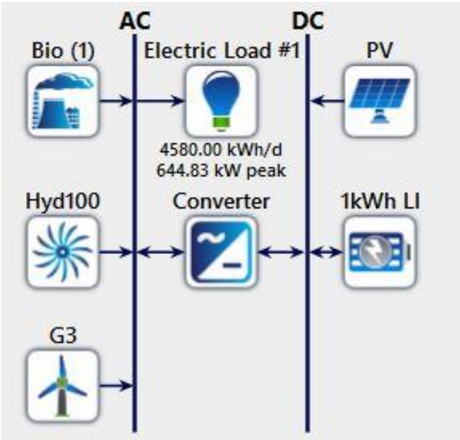

Figure 13 System schematic for simulations

A generic variant of each component was modelled, the input variables used in the simulation process are shown in Table 7. Temperature effects were modelled for PV and downtime for maintenance was considered with a surface roughness of 0.25 for the wind turbine. For the financial parameters; the discount rate was assumed to be 10.7%, inflation2.35% and a project lifetime of 20 years.[109]

Table 7 Simulation parameters used in HOMER for each component

	PV	Wind turbine	Hydro	Biomass	Battery	Converter
Capacity	1 kW	3 kW	100kW	250 kW	1 kWh	1 kWh
Capital	$2500	$18000	$460000	$750000	$550	$300
Replacement	$2500	$18000	$229900	$300000	$550	$300
O & M	10 $/year	180 $/year	$23800	15 $/op. hour	$10/ year	-
Lifespan	25 years	20 years	25	20000 hours	15 years	15 years

Derating factor	80%	-	-	-	-	-
Hub height	-	17m	-	-	-	-
Available head	-	-	25	-	-	-
Min. load ratio	-	-	-	50%	-	-
Min. runtime	-	-	-	0 mins	-	-
Fuel density	-	-	-	0.72 kg/m3	-	-
Carbon content	-	-	-	5%	-	-
CO emissions	-	-	-	2 g/kg	-	-
Throughput	-	-	-	-	3000 kWh	-
Initial charge state	-	-	-	-	100%	-
Min. charge state	-	-	-	-	20%	-
Efficiency	-	-	80	-	-	95%

3.2 AHP for system selection

The criteria used to evaluate modalities are shown in Figure 14, as well as the general hierarchy structure.

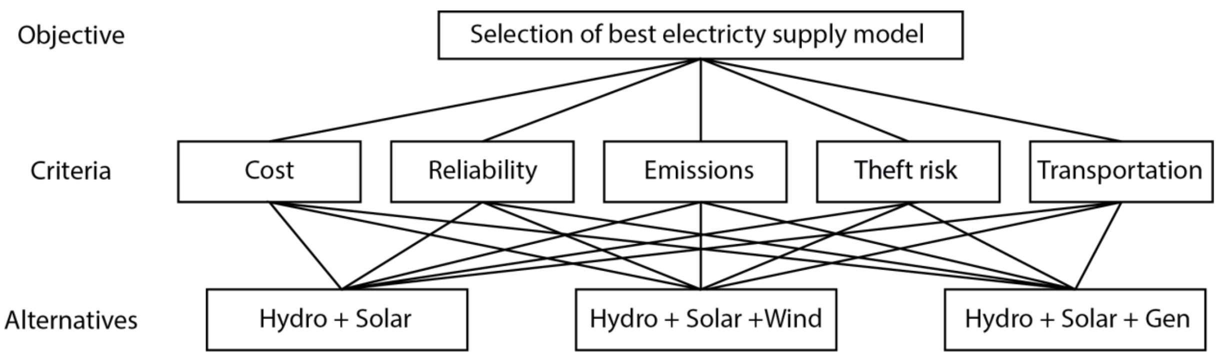

Figure 14 Hierarchical structure of the process

Each of the criteria, shown in the AHP diagram of Figure 14, were assessed by performance indicators shown in Table 8.

Table 8 Metrics used to evaluate criteria

Criteria	Cost	Reliability of supply	GHG emissions	Risk of equipment theft	Ease of equipment transportation
Measure	$	% of supply met	Tons of CO_2/year	Permanence of structure	Modularity

Due to the time restraints, and since the primary aim of this project is not to conduct a thorough AHP analysis, a limited number of experts were invited to participate. Ten participants were selected from several fields including; renewable energy engineering, civil engineering, construction management and non-governmental organisations (NGOs). Respondents were given detailed information of each of the factors regarding the provision of rural electricity and asked to rank each option of the Saaty scale. Each respondents survey was tabulated and combined with the rest of the response by taking the geometric mean of the values for each pairwise comparison.

4 Results

Table 9 shows the results of the preliminary simulations which were used to determine the performance of each system. The hydro and solar (HS) system and the combined hydro, solar and wind (HSW) systems perform comparably in terms of financial metrics. The net present cost (NPC) of the hydro, solar and biomass generator (HSG) configuration is significantly lower than the other options. The NPC is the present value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime. The resulting cost of electricity is also notably lower, as is to be expected in this situation. The annual operating costs vary by 5% between systems. This is a small contribution to the overall costs of the systems since the initial capital is the primary driver in the costs of these systems, which is clearly indicated in this table. The HSG system is able to more closely match supply and demand which is shown by no unmet demand. This is a good indicator that the supply is reliable, at least in terms of capacity and ignoring non-technical issues. Both HS and HSW have significant excess generation and fail to fully meet the demand. The HSG arrangement does, however, produce GHGs since the generator burns organic matter. Neither HS nor HSW produce any GHGs in the generation of electricity. There is of course embedded carbon in the system in the form of RET fabrication, transportation to the site and installation, amongst others. This is a complex process and outside the scope of this project.

Table 9 Results of preliminary simulations showing key parameters for each permutation

		Hydro + Solar	Hydro + Solar + Wind	Hydro + Solar + Generator
Net present cost	($ M)	8.25	8.36	3.76
Cost of electricity	($/kWh)	0.509	0.512	0.232
Operating expense	($/year)	115,340	112,295	110,281
Initial capital	($ M)	7.13	7.26	2.68
Excess generation	(MWh)	1,864	1,964	131
Unmet demand	(MWh)	1.05	0.99	-
CO_2 emissions	(kg/year)	-	-	286

To determine the system which best fulfils the design criteria AHP was used to rank the alternatives. The pairwise data was computed to generate criteria weightings and rankings shown in Table 10 through Table 14. The respondents ranking of importance for each criterion was multiplied by respective criteria weighting for each alternative and presented in Table 15. The reliability of the supply and the economic cost are primary drivers in the decision-making progress, based on the information presented here. The ease of RET transportation was a moderate factor and the emissions and risk of theft had little influence in the process.

Table 10 Rankings of alternatives with respect to cost

	Criteria weight	Criteria weight (%)	Rank
HS	0.1149	11.49	**3**
HSW	0.1822	18.22	**2**
HSG	0.7028	70.28	**1**

CRI = 0.046726

Table 11 Rankings of alternatives for the reliability of supply

	Criteria weight	Criteria weight (%)	Rank
HS	0.1026	10.26	**3**
HSW	0.2160	21.60	**2**
HSG	0.6814	68.14	**1**

CRI = 0.002278

Table 12 Rankings of alternatives for GHG emissions

	Criteria weight	Criteria weight (%)	Rank
HS	0.4663	46.63	**1**
HSW	0.4330	43.30	**2**
HSG	0.1007	10.07	**3**

CRI = 0.0047738

Table 13 Rankings ofor the risk of hardware theft

	Criteria weight	Criteria weight (%)	Rank
HS	0.1226	12.26	**3**
HSW	0.3202	32.02	**2**
HSG	0.5571	55.71	**1**

CRI = 0.015797

Table 14 Rankings of the difficulty in equipment transport

	Criteria weight	Criteria weight (%)	Rank
HS	0.6194	61.94	**1**
HSW	0.0964	9.64	**3**
HSG	0.2842	28.42	**2**

CRI = 0.074734

Table 15 The cumulative priorities for each criterion and alternative

	HS	HSW	HSG	Criteria priority
Cost	0.0397	0.0630	0.2430	0.3457
Supply reliability	0.0395	0.0832	0.2624	0.3852
Emissions	0.0296	0.0275	0.0064	0.0635
Theft risk	0.0088	0.0229	0.0399	0.0716
Ease of transport	0.0953	0.0148	0.0438	0.1539
Alternative priority	0.2130	0.1915	0.5955	

Since HSG is clearly the most favoured alternative, with almost a 60% priority, so it was examined in greater detail. The electrical production per month is shown in Figure 15. As can be seen in this figure there is little seasonal variation in terms of hydro and PV production with the biomass generator adapting output to meet demand. The noted issue with low river levels in the winter are not a concern for this system since the demand is not that high and the available resource is substantial. A run-of-river system in the Tamakoshi river would only capture a small proportion of the potential energy available.

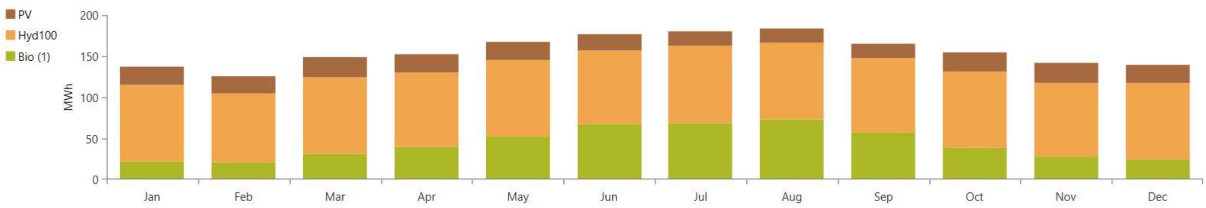

Figure 15 Monthly electrical production

Production	kWh/yr	%
Generic flat plate PV	254,901	13.6
Generic Biogas Genset (size-your-own)	522,521	27.9
Hydro	1,095,679	58.5
Total	1,873,100	100

Figure 16 Proportion of generation by source

Whilst providing just over a quarter of the total power produced, as shown in Figure 16, the biomass generator provides the key to producing dispatchable power when required and eliminating the associated costs of over sizing the system. The plot in Figure 17 shows the fuel consumption as a coloured pixel at every timestep in the operating year. Black signifies that the generator is not operating, and a red pixel denotes the generator working at full capacity. As can be clearly seen from the plot the generator provides power during peak times throughout the year, with short periods in the winter and longer stretches in the summer. There is also a noticeable increase in power demand during the monsoon season, in keeping with the increased demand shown previously in the demand profiles. This shows the generator is operating as intended and producing power to meet peaks, rather than as the baseload of the system. The generator was modelled to have a capacity factor of 11.9% and a mean electrical efficiency of 30.8%.

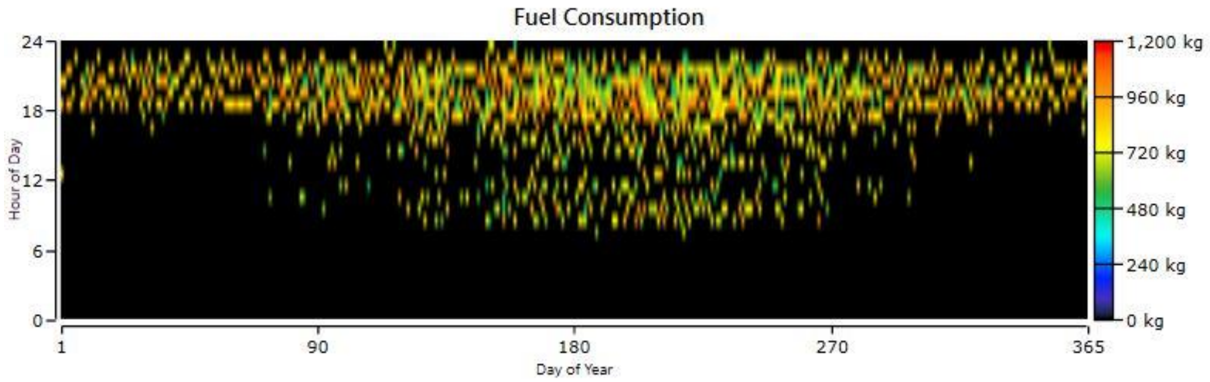

Figure 17 Fuel usage throughout the year

It is vital with a system such as this to compare supply and demand with respect to matching and not simply on a net basis.

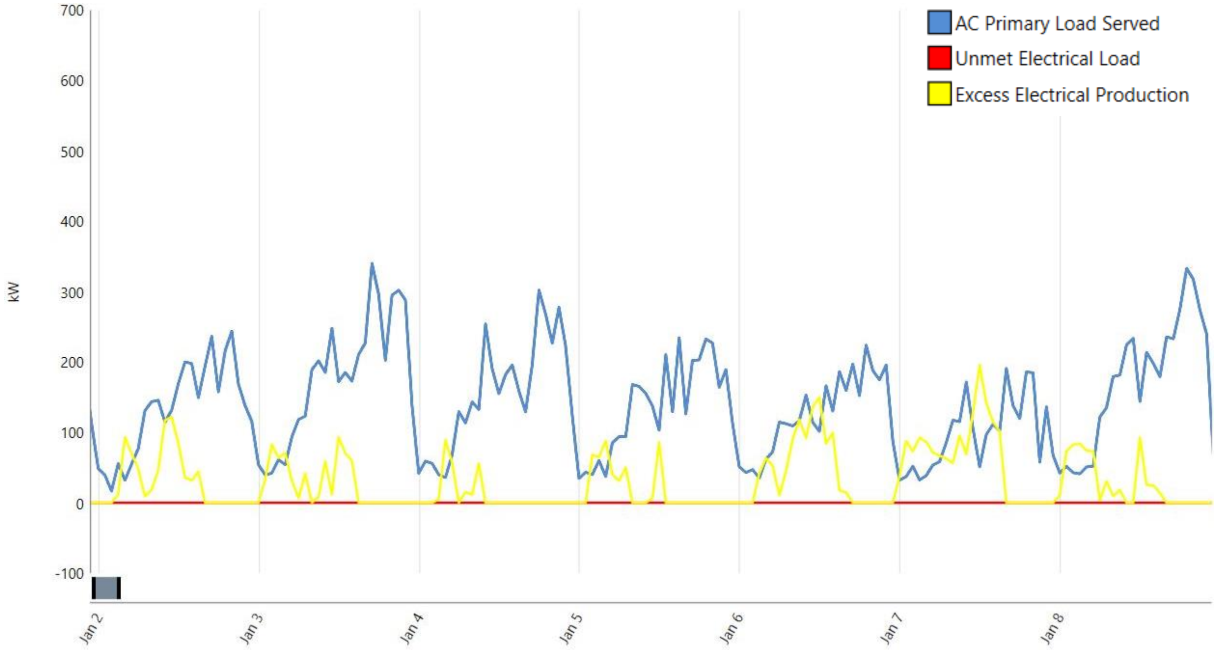

Figure 18 Characteristic daily generation for winter

As Figure 18 shows the demand grows steadily throughout the day, reaching a peak around 350kW in the later evening. The lower demand in the morning coincides with excess generation and there is no period where the demand cannot be met. A characteristic monsoon week is shown in Figure 19, the daily peaks are approximately 600kW and the excess supply is much lower.

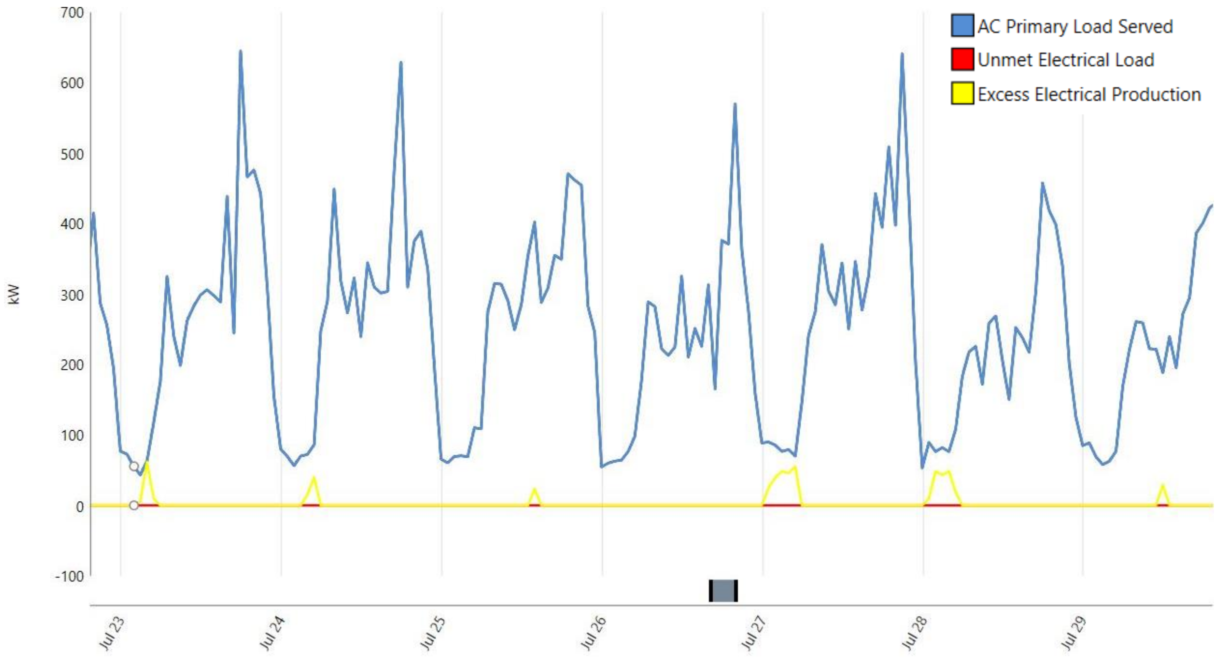

Figure 19 Characteristic daily monsoon season generation.

The increase in demand during the day is met by an increase in renewable generation. This comes in the form of solar generation and can be seen in Figure 20.

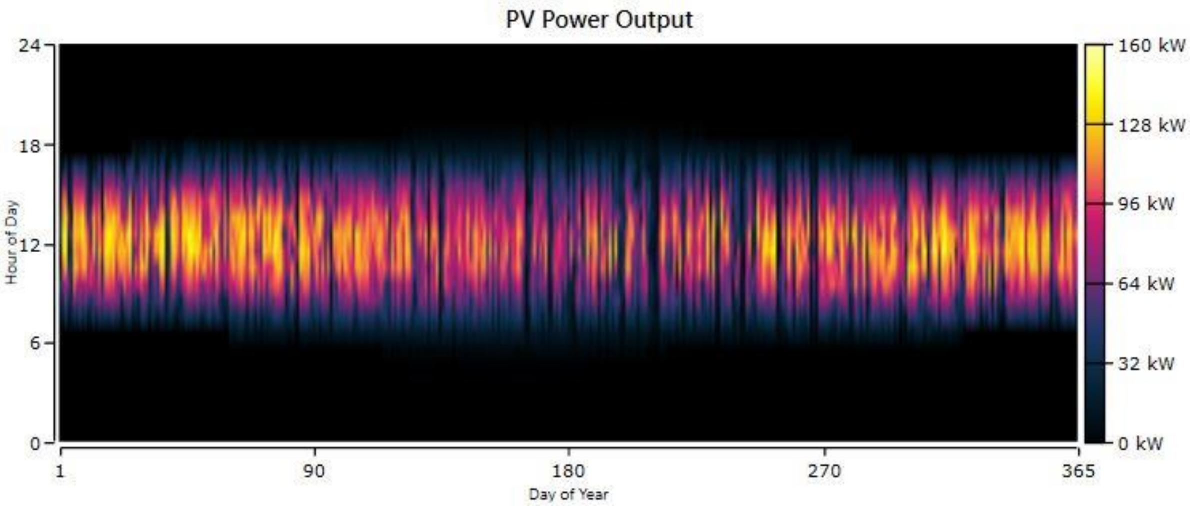

Figure 20 Solar generation

The order of magnitude of the electrical generation is consistent with the findings presented in the literature.[17,34,73,110]

5 Discussion

As with any project, and despite the authors best attempts, there are limitations to this project. The nature of remote communities means there is little data available and it tends to be non-specific or out of date when it does exist. This project has made a number of assumptions in this regard, but it is not the only one to do so. Detailed demand profiles do not exist for communities such as Jiri, especially for unelectrified ones. Generally appliance usage surveys are used to generate profiles but these are unreliable since respondents can rarely accurately quantify their behavioural patterns.[69] The climate data used in this investigation is from the NASA database, confidence is such a well examined data set is high (it is used for climate change modelling and so has been well examined) but it is not site specific. There is a meteorological station in Jiri, however, it was not possible to obtain data from this source. The authors intention was to include more social and political considerations in the AHP survey, given more resources each criterion would have been divided into sub-criteria to gain a broader understanding. The respondents to the AHP survey, whilst being experts in their respective fields, are not local residents to Jiri. This limits their intrinsic knowledge of the community, even though several of them have worked or travelled in the region.

The results of any problem are a product of the input variables and the initial boundary conditions. In this case the input variables have previously been stated and the boundary conditions are constructed from the climate variables. There is a strong correlation between the daily solar resource and PV generation, as is to be expected. The hydro production does not vary as it is an undersized generator for the available resource. Biomass-based generation fills the deficit between the demand and the production of hydro and PV electricity. There are points of excess generation during the winter mornings. Underutilised resources like decrease the economic viability of schemes since the capacity of the system is greater than is necessary. This could be combatted by either load shifting or by initiating income-generating activities.[28,84] There is a need to encourage increased consumption, especially in periods of excess generation, to make the scheme more financially attractive. This is counterintuitive with regards to the global approach to energy, where an overall reduction of energy consumption is recommended, however it makes sense in this scenario. This could be achieved by non-linear pricing which encourages the poorest customers to use more electricity.[111] This approach has been shown to be more effective than time-of-use tariffs in developing countries.[112]

The inclusion of a biomass generator does not fit with our current western ideals and concepts of how renewable energy systems should be implemented but it is vital to this system. The principle objective is to electrify the community and the GHG emissions were less of a concern to the experts in this study. However, biomass still produces lower emissions than a grid extension or conventional diesel generator. It is also important to note that the untreated dung releases methane, which is more potent GHG than CO_2, even if it is less long-lived. The purpose of applying AHP was to determine the most important factors to the community the system is designed to served, as Cloke *et* al. stated, projects are too frequently reverse-engineered through the lens of particular combinations of technologies, financial models and delivery mechanisms, rather than by attending to the particular needs and aspirations of individual communities.[41] This is a direct result of the metrics we choose to measure the project success by.

Adam Smith outlined theory of moral sentiment in The Wealth of Nations.[113] Stating that the value of any government is judged in proportion that it makes its people happy. GDP for example is a relatively crude measure for judging the welfare of a nation, which Kuznets, who proposed the system, warned. The Kingdom of Bhutan, a close geographic neighbour to Nepal, has included the concept of Gross National Happiness (GNH) in its constitution [114] and the UN has encouraged all member states to follow suit.[115]

6 Conclusions

This investigation has presented an innovative approach to renewable energy technology selection, utilising a combined AHP and simulation-based approach. This builds on previous work in the literature to provide quantifiable judgements in the decision-making process. A hydro, solar and biomass hybrid system with battery storage was deemed the most favourable solution, given the initial parameters.

This process could be applied to other energy-system selection problems, aiding in future design processes. This project found the most favourable alternative to include biomass which is not typically accepted in developed countries. It is important to consider that while reliance on traditional biomass can be perceived as energy poverty, the Nepalese case illustrates that there might be reasons, such as post-disaster recovery, why communities should be allowed to keep, or revert back, to less efficient energy sources.[116] In such cases, policymakers also need to pay attention to the needs of the population in general, and local and vulnerable communities, before implementing energy policies.

Due to the inherent time and resource restrictions of this project there are several avenues of research that would benefit from further investigation. To test the robustness of the selected system a variety of use-cases should be evaluated, including higher than predicted demands and decreases in supply, for example, due to drought. An optimization process similar to that employed by Domenech *et al.*[117]would also be beneficial. Ultimately, developing a system that integrates the approach outlined in this report with geospatial satellite imagery to tailor the mini-grid and equipment to make it site-specific. Currently, the cost of developing these projects is approximately $45000 due to site-visits from multiple experts and extensive investigations. This could be greatly reduced by applying the proposed process and integrating surveys of local residents with satellite imagery to inform the scaling of the system could increase the ease and speed to rural electrification whilst decreasing the costs.

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