Department of Mechanical and Aerospace Engineering

Design of Sustainable Energy Systems for Rural Communities in Pakistan

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Signed: Maria S Shafiq Date: 31/08/2016

Abstract

Pakistan has a high electrification rate compared to other developing countries however many residents are energy poor and suffer from daily blackouts and so rely on diesel generators. Rural communities suffer tremendously from these blackouts due to transmission losses in the grid. This report is focused on the main concepts which need to be taken into consideration when designing an energy system for rural communities in Pakistan. A case study was used consisting of three villages located near each other – Chak 111/12L, Chak 112/12L and Chak 113/12L – all in the Punjab province of Pakistan. A methodology was constructed and used throughout the investigation, to ensure efficient work was being completed. The methodology focused on a literature review, research on microgrids, energy storage and climate data. The next steps consisted of constructing a demand survey to help identify the energy consumption patterns as little information is available. This was then used to produce the demand profile that could be implemented into the model.

A literature review was completed on certain topics which were considered important: energy consumption in rural villages, energy poverty, microgrids and hybrid energy systems, benefits of providing electricity access and information regarding software. One of the methods that can be implemented to implement a secure electricity supply is through the use of microgrids. Microgrids are able to provide high renewable fractions and a reliable source of electricity if energy storage is also implemented.

There is a lack of information available on rural energy consumption, so a demand survey was constructed and completed for a sample of 20 houses. The survey showed that many house had forms of air condition, refrigeration, washing machines, cookers, lights and phone chargers. These were all considered into the demand profile, and multiple by 1000 to replicate 1000 households (for all 3 villages). HOMER (Hybrid Optimisation Model for Multiple Energy Resources) was used to model four scenarios in order to see the effect of certain financial climates on an ideal energy system.

The ideal energy systems for a rural community in Pakistan – specifically for the case study of Chak's 111-113/12L – constitutes of large PV capacity, with storage to ensure any surplus energy produced from the PV array is stored for later use. There is also a generator (diesel or biogas generator) which is part of the ideal energy system to produce any energy required to meet the deficit between supply and demand. This ensures autonomy of the microgrid system, reduced carbon emissions, high renewable fractions and lower net present costs.

Acknowledgements

This thesis would not have been possible if it were not for my dear family, so I would like to take this opportunity to highlight my sincerest gratitude to them for their constant support and financial contributions throughout my studies. Without their help and on-going support, I would not have been able to study towards this degree.

I would like to extend my appreciation to my fellow students and friends, who have helped me during times of need throughout the course. I have met some amazing people on the course who have always offered great help.

Lastly, a thank you to all of the lecturers through this program, for their passion, support and knowledge which has provided substantial help throughout my year at the University of Strathclyde.

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Nomenclature

kW – Kilowatt

W - Watt

f_{PV} – PV derating factor

Y_{PV} - rated capacity of the PV array in kW

I_T - Global solar radiation incident on the surface of the PV array

I_s - Standard amount of radiation used to rate the capacity of the PV array (1 kW/m^2)

P_{PV} – Power output for PV array

α_P – Temperature coefficient of power (%/ºC)

T_c – PV cell temperature at the current time step (ºC)

$T_{c,std}$ – PV cell temperature under standard test conditions (25 ºC)

p_{ren} – Renewable penetration (%)

P_{ren} – Total renewable electrical power output in a time-step (kW)

L_{served} – Total electrical load serviced in a time step (kW)

COE – Cost of energy ($)

$C_{ann,tot}$ – Total annualised cost ($)

E_{prim} – Total primary load

E_{def} – Total deferrable load

$E_{grid,sales}$ – Amount of energy sold to the grid per year

C_{NPC} – Net present cost ($)

$CRF(i, R_{proj})$ – Capital recovery factor for project

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1. Introduction

Electricity is a fundamental privilege but it is not readily available around the world. 1.5 billion people around the globe have no access to electricity and approximately one billion people receive access to an intermittent supply of electricity, with regular outages (Economist, 2010).

The situation is much worse in rural areas of the developing world, more than 95% of those living without electricity reside in rural areas (International Energy Agency, 2015). The residents of rural areas in developing countries are prime examples of those suffering from "energy poverty." Energy poverty is defined as the lack of access to modern energy services. The lack of energy services in the developing world is one of the most significant barriers to a country's development and prosperity, as it severely lags economic growth and development (Hepler, 2015).

Pakistan, located in southern Asia, is a prime example of a developing country that is struggling to eradicate energy poverty. Almost two thirds of the country's population reside in rural areas (DataBank, 2016). From the rural population, a significant percentage (97%) of these household's experience high degrees of severe energy shortages, which take place in the form of daily rolling blackouts resulting detrimental effect on the human welfare of those suffering. A result of the blackouts has led to increased reliance on back up diesel generators, which are used frequently to supply electricity for important appliances. Many of the rural households use alternative forms of energy, with a large dependence on biomass and back up diesel generators for heating and cooking, with candles and kerosene being used for lighting. The use of such energy sources have well documented effects as the combustion of biomass and fossil fuels release gaseous and particulate emissions which are hazardous to health and can have a prolonged effect on the well-being of a person.

For this investigation, a case study of three villages – Chak 111/12L, Chak 112/12L and Chak 113/12L – in the province of Punjab were selected. It was assumed the villages consisted of 1000 households together (with an average of 5 people per household). These villages were selected as many of the residents have access to unreliable access to electricity from the grid, and due to ease of access to obtain information which is essential for this investigation. The villages are close in proximity – as seen in Figure 1, and are located south of Chichawatni Jungle while being surround by farmland. The investigation had a main focus of providing a secure supply of electricity which would provide the residents with on-demand electricity.

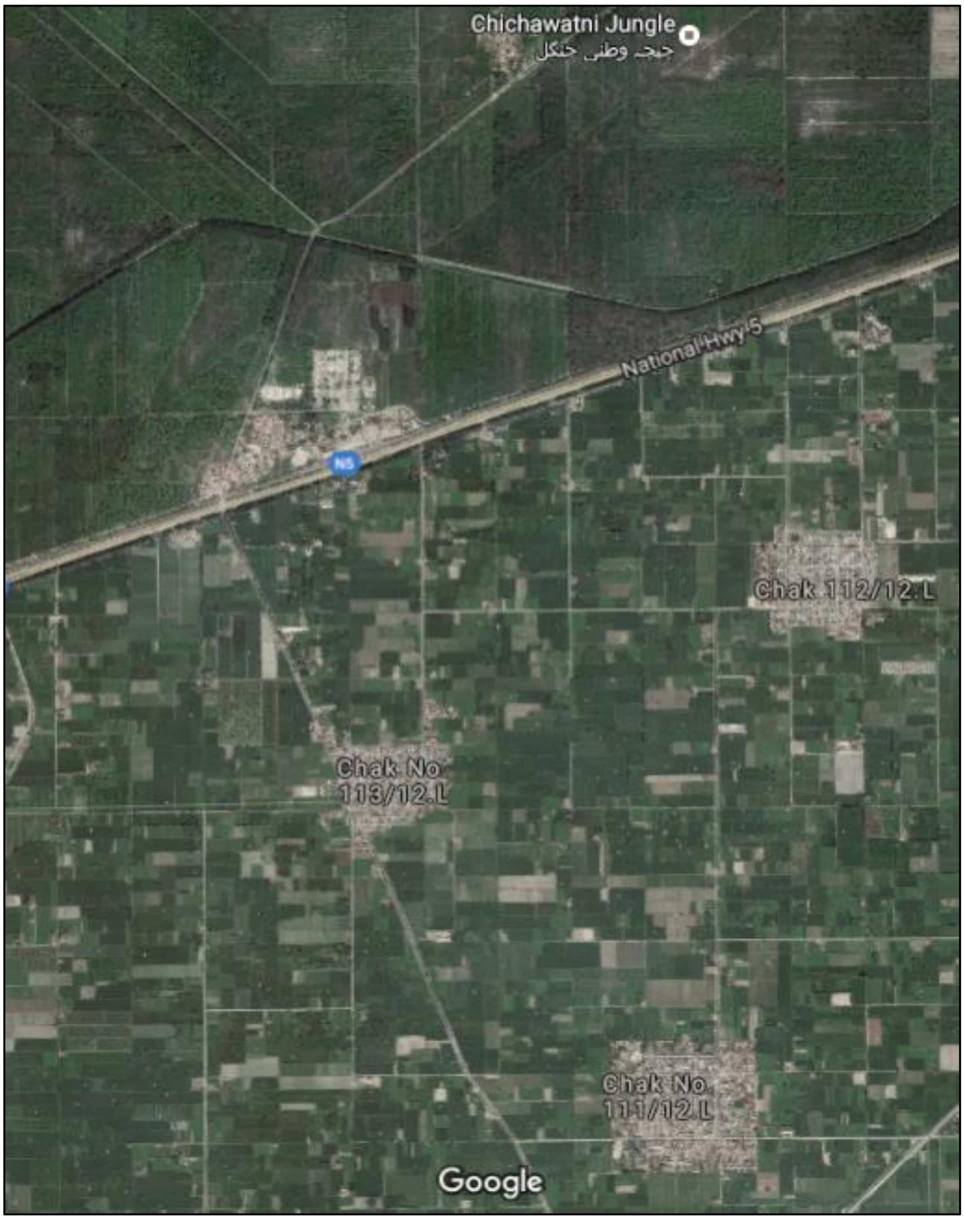


Figure 1 - Google Earth image of the villages in Pakistan

In order to provide a secure electricity access to rural villages of Pakistan, energy systems need to be implemented which not only supply electricity, but are also able to provide a reliable and secure supply of electricity. There are two possible solutions: either extend the grid to these rural areas or install microgrids. Extending the grid to these areas would not ensure a reliable and secure supply of electricity and access to modern energy services, as the national grid infrastructure succumbs to large transmission and distribution losses. Additionally, it would prove to be expressively expensive due to the large distances which would need to be covered and the many villages and rural areas which would need to be connected. Many rural villages currently have access to national grid electricity however, due to the instability of the grid – still heavily rely on diesel back-up generators.

The installation of microgrids offers a viable solution to energy poverty and would provide a resilient supply of electricity to rural communities due to the nature of the system. Microgrids have multiple advantages when applied to rural communities in comparison to extending grid connections. They are able to incorporate renewable resources with a higher penetration, hence reducing reliance on traditional fossil fuels and toxic emissions. The system will have reduced transmission and distribution losses as geographically, generation sources will be based closer to demand loads, and also promotes public participation which will have a positive impact on the local community. The use of microgrids would reduce pressure on Pakistan's current generating stations if rolled out on a larger scale, and reduce the frequently of blackouts within the country.

Rural communities would benefit greatly from microgrid technologies, as it provides the community with an environmentally sound concept, which would reduce energy poverty simultaneously. This would aid Pakistan's commitment to the Kyoto Protocol, and in turn benefit the country by enhancing a greener and wealthier image, while additionally aiding the acceleration of economic growth and development. A secure supply of electricity would benefit the community in a number of ways – from helping school children have access to lights during darkness, to mothers being able to cook without inhaling hazardous chemicals. The benefits could be endless.

1.1 Objective

The aim of this report is to design a sustainable energy system for rural communities in Pakistan.

The energy system should meet the following criteria:

- The system should be able to run autonomously;
- It should have a high renewable fraction;
- Be financially wise in regards to the future; and
- Carbon emissions should be a minimum.

The rural community chosen as a case study are three villages: Chak 111/12L, Chak 112/12L, and Chak 113/12L, located in the province of Punjab of Pakistan.

1.2 Methodology

In order to meet the objectives of this report, extensive research will need to be completed.

- **Chapter 2:** To begin with, an in depth literature review was conducted out on similar case studies in order to gain background knowledge. Countries that are similar to Pakistan with rural electrification rates and income levels were analysed to identify how energy systems are designed for the rural areas in these countries – such as India and Bangladesh. The "rural energy problem" was researched, as well as "energy poverty" and possible solutions to the issues.

- **Chapter 3:** Clarification on why micrograids were selected over grid extensions, and which form of energy storage is chosen and why.

- **Chapter 4:** The next step involved collecting climate data of Pakistan. For this investigation, the province of Punjab in Pakistan was selected, with the investigation focusing on three villages (Chak 111/12L, Chak 112/12L and Chak 113/12L) and climate information for the province was collected. Following on, identification of the various renewable energy technologies that could potentially be incorporated into an energy system. This involved research using literature and climate analysis. While completing the initial literature review, typical demands for rural villages were also collected.

- **Chapter 5:** Ideally, a site visit should have been carried out, allowing for data gathering as there is limited data available for rural villages in Pakistan. However, due to cultural sensitivities and timing of this investigation coinciding, it was not possible. Therefore, much of the data capture had to be concluded by a third party. To allow data to be collected, a survey sheet was constructed, and this survey sheet could be utilised in similar projects with minimal changes – as a template. The demand survey focused on identifying energy consumption patterns, and usages for various appliances, which in turn would help identifying the demand.

- **Chapter 6:** To allow the efficient design of an energy system, a tool assessment was completed to ensure the objectives of the report were met. The tool selected for this report was HOMER (Hybrid Optimisation Model for Multiple Energy Resources) as it was able to aid in microgrid design, optimisation and provide financial and emission data for scenarios.

- **Chapter 7:** Through utilisation of HOMER, combinations of microgrid designs were modelled and results were produced. Simulations were completed based on estimated costs in line with current values, and with a decreased cost for renewable energy technologies as this is expected in the future while diesel is expected to increase in price.
- **Chapter 8:** The results were firstly checked according to values of unmet loads. Combinations with the highest renewable penetration were further analysed based on cost and carbon emissions to identify the best available combination. The most viable combination would have to be more cost effective, release less carbon emissions and provide a reliable and secure supply of electricity that is financially viable.
- **Chapter 9:** Through analysis of the results, areas of future work on the research area was identified and a conclusion was made.

The process used for this investigation reflects each section of the report, which has been stated above. The methodology used is transferable and can be utilised in other projects.

2. Literature Review

The literature review focused on multiple components that were vital to comprehend the background knowledge of the investigation. There are five sections of the literature review that were researched in great detail:

- Rural village energy consumption – It is important to understand how the usage of rural communities differs from urban areas and how much previous research has been completed to understand the demand.

- Energy poverty – what defines as energy poverty and its effects on the communities who suffer from the issue?

- Microgrids and renewable energy – this has a recurring topic in research, as it could be a solution to supply communities with electricity. There are different system configurations, which will be discussed.

- Benefits of providing electricity to rural communities: the impacts electricity access will have on communities is important to consider.

- HOMER (Hybrid Optimisation of Model with Multiple Energy Resources) tool: some research has involved this software, and it was included in the literature review to aid in software selection.

Rural village energy consumption

The rural energy problem has many contributing factors, Cherni et al. has identified the following distinguished areas that are able to counteract the issue; technologically maximising energy supply, economically reducing costs, minimising social welfare impacts and mitigating environmental damage (Cherni, et al., 2007).

Miah et al. completed research on rural household energy consumption patterns in villages located in the Chittagong district of Bangladesh. Their findings showed that many countries including Bangladesh, and others such as Nepal, India and Myanmar household energy consumption constitutes approximately 70% of total energy consumed. A method used to collect data on energy consumption within the village was socio-demographic survey. The study focused on income levels, types of fuels utilised and the volumes used, and different housing types. As expected there are a variety of housing types available in Bangladesh from rural mud houses to modern mansions. The research conducted concluded that:

- Use of biomass and candles increases as income increases, as more money is available to be spent on energy supplies;
- Lower quality housing was correlated to lower energy consumption due to lower available income and reduced affordability of energy supplies;
- Majority of households relied solely on biomass (fire wood and agricultural waste) for cooking use;
- Limited uptake of modern fuel sources for energy due to the high associated costs; and
- Patterns of energy consumption in households are heavily influenced by the household income, however many other factors also influence choice of energy fuel.

There are many factors which affect household energy consumption in rural villages, to encapsulate the main factors, they are income level, family sizes, housing types, and education (Miah, et al., 2010).

Mustonen conducted similar research in Laos Peoples Democratic Republic in a village which had existing access to renewable energy sources and a diesel generator. As data was not readily available for the village, it was collected during interviews with the residents of the village and collecting data from relevant organisation. The interview has three parts:

- The first part focused on basic household activities and their timing;
- The next section of the interview focused on the household energy services and fuels used; and
- The final section of the questionnaire concentrated specifically on lighting, timing and any seasonal changes in lighting (Mustonen, 2010).

The energy demand of the village was similar to the findings of Miah et al. concerning fuel selection for cooking. From the interviews it was recognised that the main cooking fuel for a majority of the houses (80%) was biomass -firewood in particular (Miah, et al., 2010). However, it was also found that biomass was used for lighting, in addition to kerosene and candles, also found in literature by Karekezi and Kithymo (Karekezi & Kithyoma, 2002). Overall, the research found that energy consumption patterns for the rural village in Lao was seen to be expectedly similar to the findings in previous literature as biomass accounted for a significant fuel choice among the residents.

Kaygusuz states in his research findings that rural communities meet their lighting requirements using kerosene and electricity which is slightly contradicting previous findings. However, he does highlight that poorer communities will have increased likelihood of using low efficiency traditional fuels. He states that a small amount of rural communities, examples such as China and Japan, whom have access to grid connectivity still opt for biomass burning for cooking and kerosene for lighting as the grid connected electricity can be 10 times more expensive than more traditional fuel sources and is seen as a luxury expense (Kaygusuz, 2011).

Karekezi and Kithymo have shown through their research that biomass is a dominant energy source in many African countries which have a high percentage of rural population. Again, their research continues by discussing the correlating health issues surrounding combustion of large volumes of biomass. Due to the gaseous and particulate emissions, which are emitted during combustion, there can be a decreased resistance to respiratory infections, particularly for women and children as collecting fuel for cooking is seen as a woman's job in the culture of many of these communities (Karekezi & Kithyoma, 2002). Jan et al. have found that women can spend up to 6 hours per a day collecting firewood for burning (Jan, et al., 2011). The health effects of the continued burning of biomass as also been reiterated by Kaygusuz's research, Mondal, Kamp and Pachova's findings, and by literature produced from Jan, Khan and Hayat. Their literature has stated "3% of global burden of diseases are caused by indoor pollution" leading to millions suffering from chronic respiratory diseases, breathing issues, sinus problems among other illnesses (Kaygusuz, 2011) (Jan, et al., 2011) (Mondal, et al., 2010).

To summarise the findings on the energy demands and fuel choices for rural communities, it is easily seen and reinforced by many researchers that a large amount of energy consumed in rural households is used for cooking purposes, with the remainder being used to meet the requirements of lighting in these households. Biomass was the most common type of fuel used for cooking requirements which, can have adverse health effects on women and children as they spend the most time around the emissions produced from combustion, while lighting requirements were typically met by kerosene lamps, candles and electricity.

Energy poverty

Awan, Sher and Abbas have stated that energy poverty, defined by the World Economics Forum, is:

"The lack of access to sustainable modern energy services and products"

To express in greater depth, it can be explained as a situation when the access to adequate, reliable, affordable, safe and environmentally suitable energy services is in jeopardy and not readily available. Simply put, it can be described as the lack of access to suitable energy services and products (Sher, et al., 2014). Kaygusuz states that progress has been significant in East Asia and Latin America: however, countries in South Asia and Sub-Saharan Africa lag behind in progress. He also illustrates energy poverty as a "*vicious circle"* as many residents with low incomes will have less to spend on energy services, in turn energy companies will be reluctant to extend grid connections to the poorer villages and the lack of electricity supply inhibits growth in the local community (Kaygusuz, 2011). Awan, Sher and Abbas share analogous views with Kaygusuz, as they highlight a strong connection between energy scarcity and poverty.

Many rural areas in developing countries have significantly lower electrification rates, for a select part in Africa it is commonly 2% or less as found by Karekezi and Kithymo (Karekezi & Kithyoma, 2002). In Pakistan specifically, Mirza and Szirmai found that over 96% of rural household's experience severe energy shortages, which is a form of energy poverty (Mirza & Szirmai, 2010). Zaigham and Nayyer explains in more detail that rural areas in Pakistan have no electrification facilities primarily due to high associated costs of extending national grid connections over a large distance (Zaigham & Nayyer, 2005).

The effects of energy poverty have been recorded by Jain as having detrimental effects on many aspects of human welfare; agriculture productivity, access to water, education, health care and job creation. This has been reinforced by Kaygusuz as he states that access to electricity is a key element for the development of rural communities, especially to aid the eradication of poverty as lack of access aggravates poverty in rural regions (Kaygusuz, 2011). The importance of alleviating energy poverty has been a common theme among literature. Awan, Sher and Abbas provide an excellent example of the consequences as a result of access to sustainable, clean and reliable electricity for women, as less time will be spent collecting traditional firewood for burning allowing the time to be more effectively utilised. They also effectively highlight that if energy poverty were alleviated, it would enhance industrial activities creating more job opportunities and in turn developing the country (Sher, et al., 2014).

Energy poverty is identified as lack of access to modern energy services and is more prevalent in developing countries where electrification rates are lower. Those who are suffering from energy poverty will also suffer from the consequential impacts that will affect the economy and human welfare.

Microgrids and renewable energy

Ding, Liu, Lee and Wetz discuss two options to improve energy poverty in their research; extension of grid connections or build a microgrid incorporating distributed generation and energy storage for the supply of energy for local demands. They iterate the benefits of microgrids over grid extensions as power supplies are geographically closer to local loads. Nguyen shares analogous views as promotes microgrids over extended grid connection due to the following benefits (Ding, et al., 2013):

- Located closer to demands so transmission and distribution costs are significantly lower;
- Energy and capacity costs are lower;
- Microgrids which incorporate renewable energy technologies function independent of fuel supply and so are not affected by fuel availability;
- Creation of more employment opportunities;
- Reduction of emissions and pollutants; and
- Overall increased development and strength of local economy.

Bhoyar and Bharatkar envision that a microgrid concept could be the ideal solution for rural electrification as it will enable small rural communities to obtain control of their energy use and reduce toxic emissions through a "*new and innovative method of energy generation and management.*" They have also emphasised that microgrids provide an opportunity for high quality and reliable energy generation for communities through high penetration of distributed generators (Bhoyar & Bharatkar, 2014). For rural communities, microgrids would operate in an islanded mode, and have an additional benefit that allows them to be connected to the main grid in later years if desired as mentioned by Ding, Liu, Lee and Wetz (Ding, et al., 2013). The microgrid concept includes a network of small-scale distributed energy resources like fuel cells, micro turbines and renewable energy technologies which can be utilised bringing additional sustainable developments as mentioned by Bhoyar and Bharatkar (Bhoyar & Bharatkar, 2014).

Renewable energy systems have the potential to provide the most sustainable and cost effective electricity supply to those living in rural communities as highlighted throughout research conducted by Ding et al. Although, Akikur et al. have provided a delicate insight as to why renewable energy technologies have not been utilised to a higher potential - the initial costs associated with renewable energy technologies are significantly higher when compared to fossil fuels, as a result fossil fuels are still relied upon to produce 80% of the world's total demand (Akikur, et al., 2013). This view is strengthened by Schlapfer's research, which reasons that the low rates of rural electrification using renewable energy are due to expensive equipment costs (Urmee, et al., 2009).

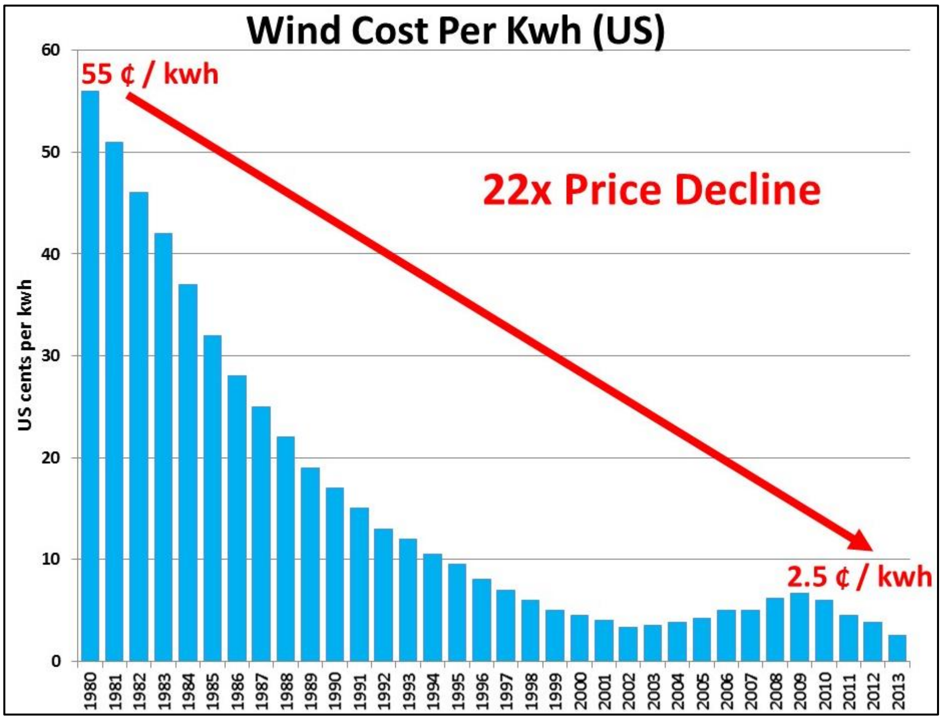


Figure 2 - Wind Turbine Cost Curve (Naam, 2014)

However, Naam has discussed the dynamic changing costs of wind and solar technologies. Figure 2 and 3 show the cost curves for wind energy and solar energy respectively. Wind energy costs have decreased drastically to 5% of the cost in 1980, and this decrease is expected to continue into the future. The same trend has been recognised from solar technology. As more research and investment is committed to solar technology, there have been more advancements leading to lower costs. This will increase applicability for renewable technologies in poorer communities, and so will increase the density of solar and wind power in the future. Diesel on the other hand is said to increase in the future, due to limited supply of fossil fuels. Although diesel may be heavily relied on now, it is expected to soar in prices. It will become more beneficial in the future to utilise renewable power over combustion of fossil fuels.

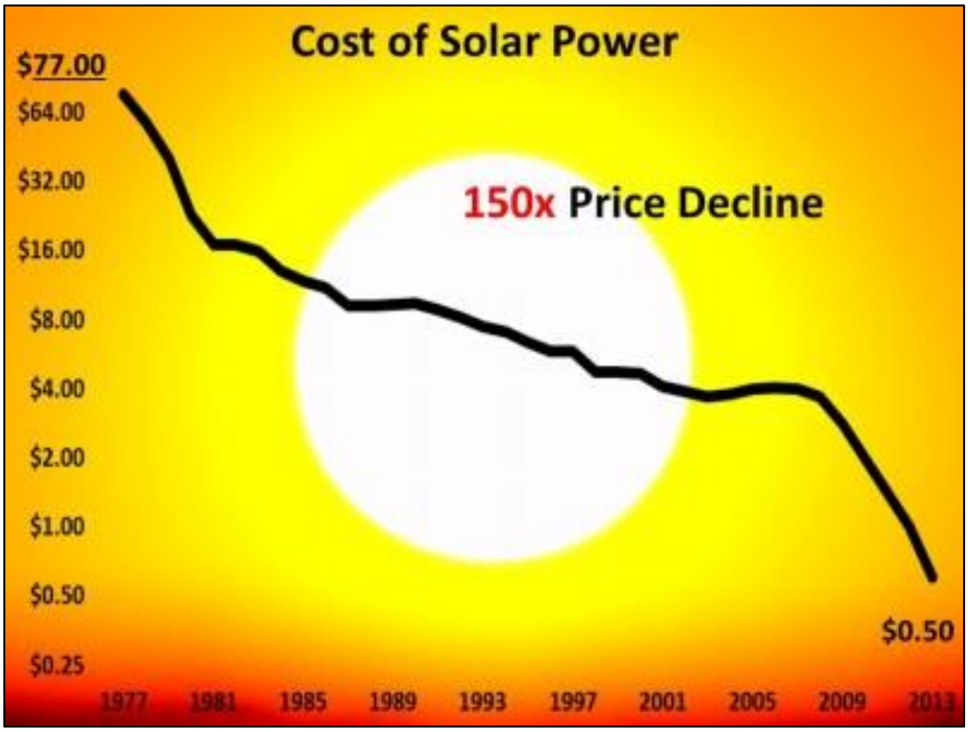


Figure 3- Solar Cost Curve (Naam, 2014)

Wichert also counteracts the argument that renewable energy technologies are the only alternative option for communities which are heavily reliant on biomass combustion. Specifically, he projects that hybrid systems will be an integral part of the movement to supply electricity to remote unelectrified villages, as seen in India (Wichert, 1997). Mondal Kamp and Pachova summarised the desired characteristics a renewable energy technology should possess in order to be successful in rural applications, the system should:

- Be simple;
- Provide a comfortable life;
- Save human energy and time;
- Increase income generation;
- Be an appropriate technology – completely controlled by humans;
- Be technically feasible;
- Be financially viable; and lastly; and
- Be ideally sustainable.

They have also additionally for successful implementation of a renewable energy systems, there should also be availability of relevant knowledge and skills required to maintain and repair the specific renewable energy system (Mondal, et al., 2010).

There have been on-going discussions regarding whether renewable energy systems should be composed of one system alone, or whether a hybrid system involving different types of renewable systems should be adopted. Akikur et al. produced research that compares hybrid renewable systems to standalone solar systems. The findings of the research reflected that in order for either system to be effectively functional energy storage is required. The energy storage will need to have the following conditions in order to be utilised in either system:

- Low cost;
- High energy efficiency;
- Long lifetime;
- Low maintenance;
- Self-discharging; and
- Simple operation.

A cost analysis was investigated on both systems, and it was acknowledged that even though both systems would produce cleaner energy, the hybrid renewable system cost remains steady with increasing distance from grid connections, and so would perhaps be more suitable for rural applications (Akikur, et al., 2013). This has also been demonstrated by Wichert as it has been found that hybrid systems reduce total life cycle costs compared to stand-alone power generation while simultaneously increasing energy reliability (Wichert, 1997).

Fong discusses the advantages and disadvantages of solar, wind and hydro energy technologies. To summarise Fong suggests that the advantages of solar energy outweigh the disadvantages for rural applications, however for wind energy to be effective it is of utmost importance that the location selected possesses suitable wind speeds due to the high associated costs. With regards to hydropower, it is only suitable if the location is ideal. He suggests that a combination of all systems – depending on location - could be very advantageous to rural communities (Fong, 2014). Nakata, Kubo and Lamont have also indicated that stand-alone renewable energy systems are not reliable, as renewable energy sources are intermittent and so a hybrid incorporating a combination of renewable sources is the favourable option (Nakata, et al., 2005). The use of hybrid renewable energy systems has been further strengthened by research completed by Byrne, Shen and Wallace in rural China. Their research was conducted in a remote district, which had large distances from grid connection, and it was found that an ideal energy system would be a hybrid renewable energy system incorporating solar and wind resources with units for energy storage (Byrne, et al., 1998). Nakata et al. produced a model utilising multiple renewable energy sources and applied it to a village in Japan. The results from the model showed that integrating renewable sources reduced CO2 emissions in half and reduced the cost of the energy system by approximately £2.3 million again highlighting the benefits of a hybrid system (Nakata, et al., 2005).

There have been arguments against the use of standalone solar photovoltaic technologies to be applied in rural applications as Karekezi and Kithymo have said that the expensive costs of solar technologies are not worth the value as the electricity produced can typically only be used for lighting and low voltage appliances. Using Sub-Saharan Africa as a prime example, they discuss how the region has implemented multiple solar photovoltaic projects however this has not been followed with an increased access to modern electricity as electrification rates are relatively low in rural areas. They go on to discuss that with the increased implementation of solar technologies there has not been a reduction in the usage of biomass in rural households, and so it will have little effect on the human welfare of the residents (Karekezi & Kithyoma, 2002). Wichert argues that although photovoltaic generators are more expensive they operate more efficiently when compared to wind generators. He also states that due to the high costs of both technologies, there is limited uptake in rural areas when governments have not subsidised renewable technologies. Hybrid energy systems could also include a diesel generation source according to Wichert, with the integration of a renewable source and energy storage to aid the diesel generator (Wichert, 1997). These forms of hybrid systems have been implemented in rural villages in Lao as discussed by Mustonen (Mustonen, 2010).

The most viable option to the rural energy problem is to construct a microgrid using multiple renewable energy technologies – a hybrid system. There are many advantages of constructing a microgrid over grid extensions, especially when implementing renewable energy sources as it will reduce reliance on fossil fuels, greenhouse gas emissions and enhance public participation in energy generation. Hybrid systems will also be more cost effective and sustainable in the long term.

Benefits of electricity to rural households

Providing rural communities with electrical access will evidently have numerous positive impacts that has been repeatedly reflected throughout literature. Kaygusuz emphasises the importance of electricity by stating that:

"Universalisation of access to electricity in the world is of fundamental importance for the eradication of poverty and reduction of social inequality."

Access to modern energy services would benefit the residents in more ways than just in their households; the benefit would also be to income-generating activities for the local residents. Kaygusuz has highlighted this concept in his research by reiterating stating rapid agricultural and economic growth is the driving force behind the reduction most of Asia and effectively connects access to modern energy services to increase agricultural productivity and income. Electricity aids irrigation water pumping, mechanization of agricultural and transport of products. The use of renewable energy technologies has been successful in meeting the needs of agricultural in rural parts of Africa (Kaygusuz, 2011). Karekezi and Kithymo have mentioned a number of processes that can utilise renewable energy:

- Solar crop dryers;
- Small hydro plants;
- Solar water pasteurisers;
- Biogas plants;
- Fish drying;
- Beer brewing;

- Charcoal production; and
- Wind power utilised for irrigation.

Providing modern energy services to rural communities would also decrease energy inconvenience significantly (Karekezi & Kithyoma, 2002). Mirza and Szirmai have identified energy inconvenience through the following indicators:

- Frequency of buying/collecting fuel;
- Distance from household travelled;
- Type of transport used;
- Household member's involvement in energy procurement;
- Time spent on energy collection per week;
- Household health; and
- Children's involvement in energy collection.

Through reduction of energy inconvenience, there are multiple consequential benefits such as increased available time for income generating activities, increase in indoor air quality and children's time being more efficiently spent (Mirza & Szirmai, 2010).

Pachauri has similarly recognised a positive relationship between wellbeing and use of clean, efficient energy (Pachauri, 2004). Jan et al have highlighted the many problems due to the combustion of biomass. The introduction of electricity services would decrease the emissions produced from biomass combustion and in turn, reflect a dramatic reduction in chronic respiratory diseases, asthma, breathing difficulties, sinus problems and low-birth weight babies. This will have a significant improvement on women and children as they spend much of their day collecting fuel sources (Jan, et al., 2011).

There are numerous benefits to providing electricity to rural communities. It will improve human welfare through reduction of energy inconvenience and enhance the growth and development of the local economy. Women who tend to spend majority of their time collecting fuel will have more time to commit to income generating activities, and there will be a notable improvement on the health of women and children. Overall, access to modern energy services would aid to alleviate poverty in these communities.

HOMER tool

HOMER (Hybrid Optimisation of Model with Multiple Energy Resources) has been developed by the HOMER Energy team, and has been utilised in similar scenarios of providing off grid electrification. Sen and Bhattacharyya completed an investigation of providing off-grid renewable electricity to a rural village in India, and preferred HOMER as a tool as it is able to handle large sets of data in hybrid combinations. Their research provides a framework of analysis which can be applied to similar studies and provides an excellent comparison of off-grid electricity to grid connections (Bhattacharyya & Sen, 2014). Cherni et al. criticises the use of HOMER as it judges outcomes based upon technical and economical merits only, and does not take into consideration of social or environmental impacts (Cherni, et al., 2007).

However, newer versions of HOMER include environmental considerations and so it is an excellent tool to utilise, although it does have limits which need to be taken into consideration through the investigation.

The competencies and underlying calculation basis of HOMER was described by Lambert (Lambert, et al., 2006). Lambert provides the equations used for the renewable technology in HOMER. For PV array, it was assumed the temperature coefficient is zero, so the power output is determined by:

Equation 1 - PV array power output equation

$$P_{PV} = f_{PV} Y_{PV} \frac{I_T}{I_s}$$

However, if the temperature coefficient is considered, the power output is determined by:

Equation 2 - PV array power output considering temperature coefficient

$$P_{PV} = f_{PV} Y_{PV} \frac{I_T}{I_s} \left[1 + \alpha_P \left(T_c - T_{c,std}\right)\right]$$

As the aim of the investigation is to increase renewable generation in rural communities and reduce reliance on diesel generators due to the carbon emission produced and the limited reserves of fossil fuels, it is important to calculate the renewable penetration. The renewable penetration is defined as the fraction of renewable power to load in a time-step.

Equation 3 - Renewable Penetration

$$p_{ren} = \frac{P_{ren}}{L_{served}}$$

HOMER is able to consider financial aspects of an energy system, which is an additional benefit to the system. The COE (cost of energy) is calculated in HOMER, using equation 4, as it provides an indicator of the financial feasibility of the system.

Equation 4 - Cost of energy

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}}$$

The NPC (net present cost) is also considered HOMER as it emulates the life-cycle cost of a system. NPC concludes all the total costs and revenues of the system within the project lifetime into a single lump sum, allowing it to be a reasonable financial representative of the system.

Equation 5 – Net present cost

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\ (i, R_{proj})}$$

When analysing the system, both COE and NPC were considered, however it was noted that the NPC provides an accurate indicator of viability. All of the equations used were provided through Lambert's literature (Lambert, et al., 2006).

The literature review provided thorough background knowledge – with importance given to the factors mentioned previously. This has helped the investigation and understanding of the important factors that need to be considered when designing a sustainable energy system for rural communities.

3. Microgrids

A microgrid can have many definitions; however it can be broadly defined as

"An energy system which consists of distributed energy sources (storage and generation) and loads. These energy systems can operate independently of the grid and synchronous with the grid providing them with full flexibility and control. (Balance Energy, 2015)*"*

The ability to switch between operating independently and synchronising with a larger grid provides reliable and more secure electricity to the receiving community, additionally it can also improve the quality of electricity as there are minimal losses due to close proximity of generation sources to loads. Microgrid installation has the potential to transform the future of electricity, as the characteristics of the system aid to decrease disturbances and strengthen the supply of electricity. The system is cost effective and competitive and promotes consumer participation and control within the system (Balance Energy, 2015). The system is able to shed loads in scenarios where demand is higher than supply. It is able to do this by ranking demands in terms of importance and shedding the least important loads, allowing the important demand loads to be met (US Department of Energy, 2011).

Implementing renewable energy sources in a microgrid provides additional benefits by reducing reliance on traditional fossil fuels, in turn reducing carbon emissions and providing a source of sustainable energy. The system provides a simple way to coordinate the increasing amount of sites that will generate electricity locally and is able to supply rural areas around the world with electricity. As a microgrid covers a relatively smaller area compared to the national grid, there is little distance between generation sources and demand loads, resulting in minimised transmission and distribution losses (Gao, 2015). The benefits of the system allow it to provide a robust and reliable electricity supply as it can be isolated from faults – increasing security of supply – and have increased penetration of renewable resources compared to traditional methods of energy generations in larger national grids (Gao, 2015).

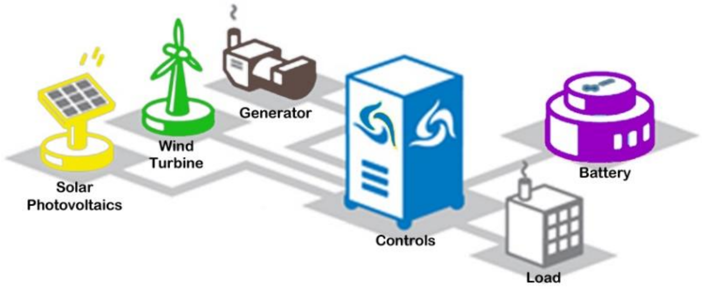


Figure 4 - Components in a Microgrid (Walsh, 2014)

A functional microgrid is comprised of many controllable components, such as:

- Renewable sources
- Dispatchable sources
- Energy storage systems
- Demand management systems
- Control scheme – which manages operation modes.

All of these components working together ensure the systems operates effectively. A microgrid can operate in two modes – islanded (autonomous) or connected to the grid (non-autonomous).

Although microgrids have many benefits, as discussed previously, they also have technological issues, as with any upcoming technology. As controlling multiple distributed energy resources and loads is an extremely complex task, this can be relatively difficult for a microgrid system to achieve, especially as it would require enhanced dynamic control (Gao, 2015). Although microgrids are able to have a high renewable integration, this can lead to complications with the planning and operation of the system due to the intermittent nature of these energy sources. Lastly, as there is higher integration of renewable sources and microgrids are a relatively new technology there are more doubts surrounding the costs of operation and maintenance (Gao, 2015).

Microgrids have the ability to transform the world of electricity, as the concept promotes local generation, reduced transmission and distribution losses, increased control and participation from the end user and high renewable penetration. However, there are current issues with the emerging technology associated with costs of operation and upkeep, high renewable integration and complexity of the technological control systems. With consideration of all these factors, a microgrid may be better utilised in areas where current grid infrastructure is not as developed, as Platt, Berry and Cornworth have said:

"The most economic use of microgrids remains in developing countries. (Platt, 2012)*"*

3.1 Energy Storage Technologies

Including renewable technologies microgrid has many benefits, however due to the intermittent nature of these renewable resources an electric system can become unstable. A remedy for this problem is including energy storage technologies in the energy system. There are numerous technologies available that can be implemented into a system, such as batteries, super capacitors, flywheels and pumped hydro.

Pumped Hydro

One of the most established technologies for energy storage is the pumped hydro. When excess (or cheap) electricity is produced, water is then pumped from the lower reservoir to the upper reservoir, which can be allowed to pass down to the lower reservoir from a height, generating electricity to the grid when required. Pumped hydro storage is the most popular type of energy storage globally, with a global storage capacity of 127 GW in 2012 (The Economist, 2012). Figure 5 depicts the infrastructure of a pumped hydro storage facility in Cruachan, Scotland.

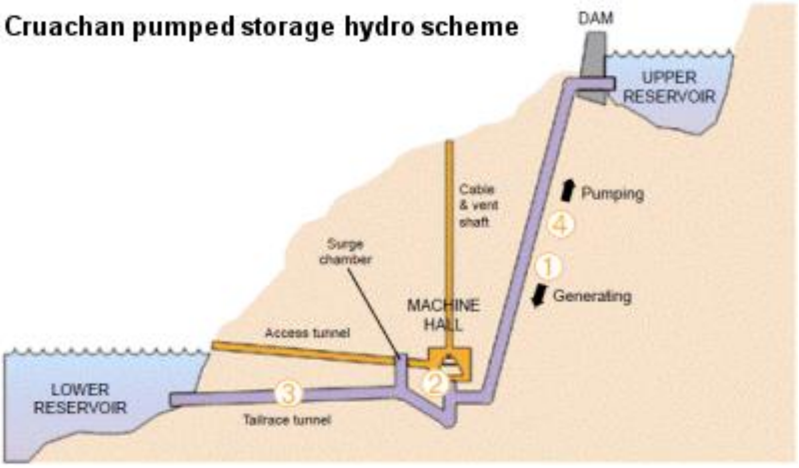
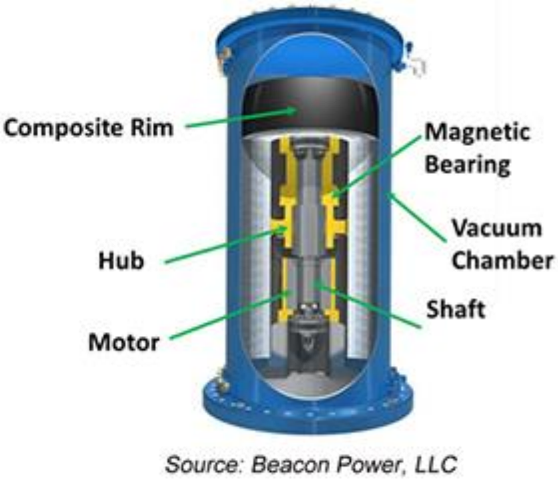


Figure 5 - Cruachan Pumped Storage (Scotland's Renewable Energy Guide, 2011)

With its popularity, it is easily recognised why pumped hydro is a common choice of energy storage, however it is not without its downfalls. It requires a large area of land, and is expensive to build. Another issue is that hydro storage cannot be built in any location and requires a specific terrain which may not be applicable to each location *(Abhishek Shah, 2011)*.

Flywheels

Flywheel technology stores electric energy in the form of kinetic energy, through rotations with low frictional loses. This technology is a compact and versatile grid stabiliser, helping to improve the integration of large amounts of renewable integration in systems (ABB, 2016). . Figure 6 reflects the inner workings of a flywheel. There are many benefits to implementing flywheel technology as they are low maintenance, their operation has zero negative impact on the environment and have long life cycles (Energy Storage Association, 2016).



Source: Beacon Power, LLC

Figure 6 – Typical Flywheel Structure (Energy Storage Association, 2016)

Supercapacitors

A supercapacitor is a mix of a capacitor and a battery, however it uses electrodes and a special electrolyte. It has an unlimited cycle life, with quick charging and is a cost effective technology for storage. However, supercapacitors have a low energy density compared to a battery as it can only hold 10-20% a batteries capacity. There is also an added complication as they require voltage balancing if three or more are connected in a series, and to attain higher voltages serial connections are required (Delonix, 2016).

Batteries

The most recognised form of energy storage is battery storage - a rechargeable form of energy storage which uses chemical energy as a form of storage for electrical energy. There are many different types of batteries, each with their own unique advantages and disadvantages for use.

Batteries are the most economical type of storage option for energy and are most suitable for off-grid applications where high renewable penetration is desired (IRENA, 2015). There are future predictions that batteries will reduce in costs and increase in reliability with on-going research and development (Divya & Ostergard, 2009).

Suitable storage technology for rural application

There are many energy storage technologies which can be installed into a system. Figure 7 shows a comparison of various energy storage technologies according to their power density, storage volume and energy density. For off-grid rural applications, storage volume is important as it will allow for maximum storage capacity in a small area. A system that is rechargeable and reliable is also desired, while attaining a suitable energy and power density. From the comparison, the most suitable option is between a fuel cell and a Lithium-ion battery. As the fuel cell has a smaller range of power density, while the Li-ion battery has a larger range for power and energy density. It also has 100% usable capacity at any discharge rate and has 100% efficiency compared to other batteries (PowerTech systems, 2015).

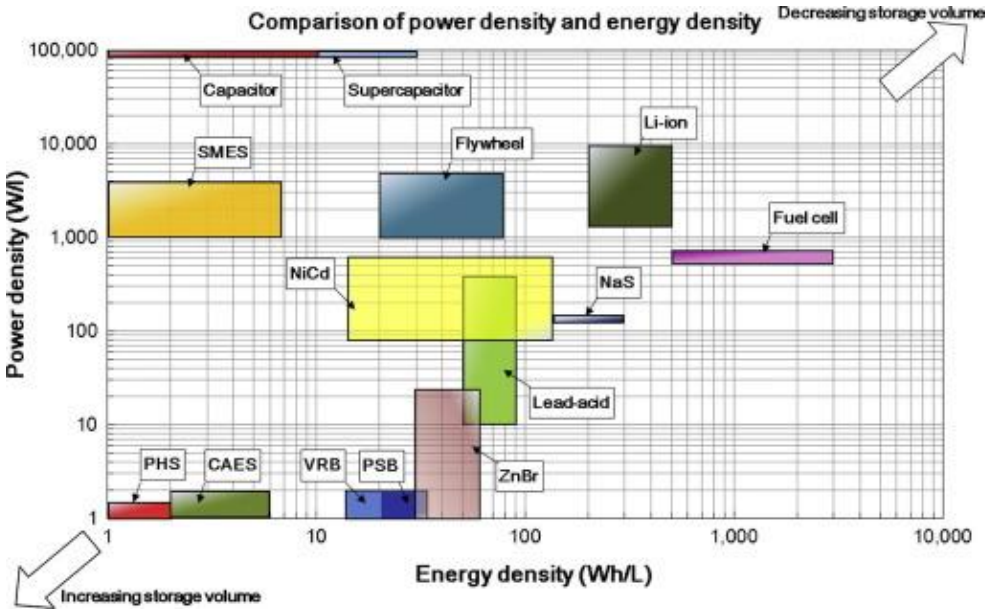


Figure 7 - Comparison of Energy Storage Technologies (Luo, et al., 2015)

In order for a microgrid to attain high renewable penetration, and remain stable to provide a secure electricity supply – energy storage is vital. The ideal form of energy storage is the use of a lithium-ion battery that has 100% efficiency compared to other batteries in addition to having a flexible range of power density.

4. Pakistan and Electricity Generation

Pakistan – a country known for its rich natural culture and invigorating natural beauty – is located in southern Asia. It has a dense population of 190 million (Economics, 2015) spread over its varied landscapes of deserts, forests and mountainous terrain.

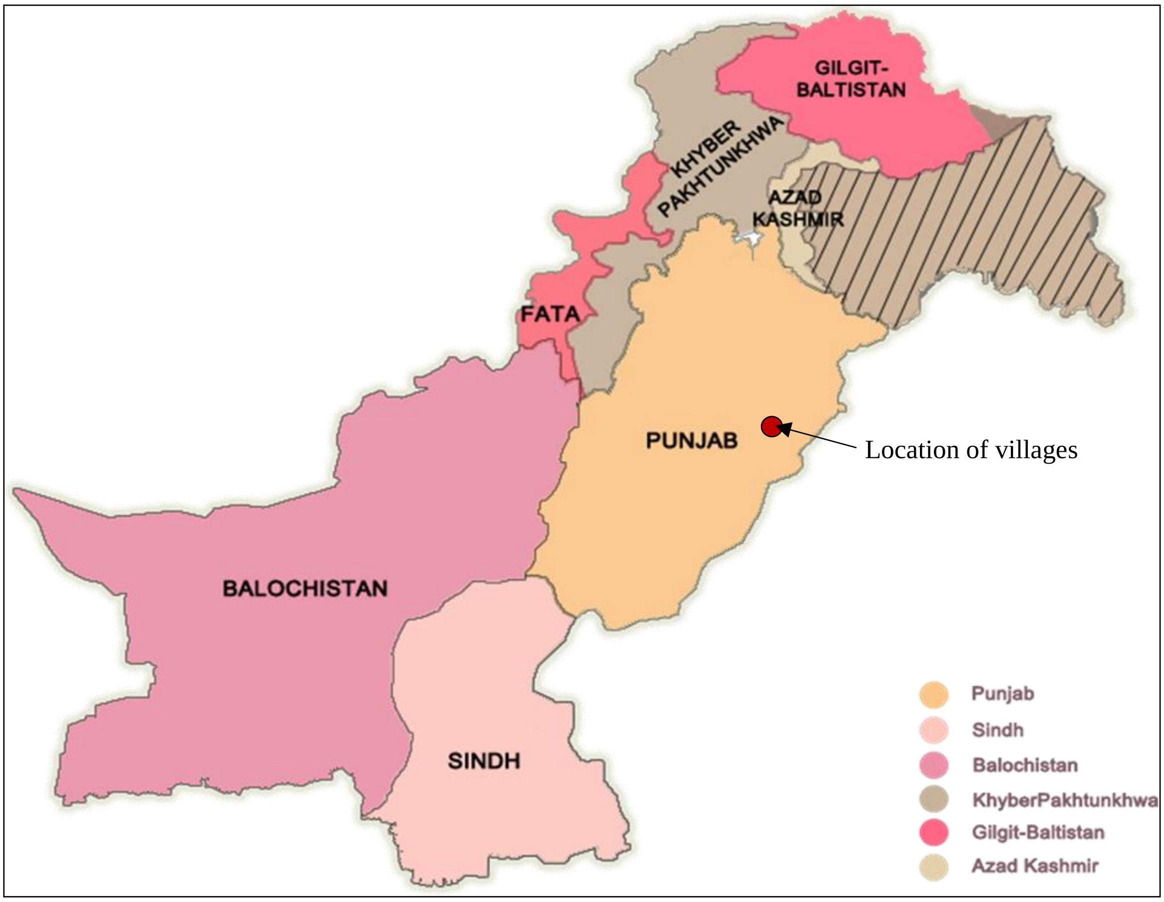


Figure 8 - Provinces of Pakistan

Pakistan had a predominantly rural population upon independence, and today the rural population still constitutes for 62% of the total population (DataBank, 2016). The rural population constitutes 80% of the poorest in the country, and so poverty of all types is evident in these rural communities (Rural Poverty Portal, 2014). The country is divided into number of provinces as depicted in Figure 8. Punjab is the second largest province in Pakistan with over 90 million populations, and has significant rivers throughout the province which are descendants of the Indus River. The villages selected from the province as a case study are Chak 111/12L, Chak 112/12L and Chak 113/12L. The approximate location of these villages are reflected in Figure 8, while a Google Earth shot shows the close geographical proximity of the villages in Figure 1 (Chapter 1).

The country has been infected with political instability, which has resulted in a tremendous strain on its electricity grid as many projects to increase capacity of energy supply have been dropped and/or neglected. Pakistan has an installed capacity to produce over 23,000 MW (Kazmi, 2014) of electricity, but this capacity is insufficient enough to meet the national demand. Currently those who live in urban areas of Pakistan still experience black outs for a significant number of hours throughout the day, while those who live in the rural areas are considered the ‘lucky’ to even be graced with two or three hours of electricity in a day if they are connected to the grid.

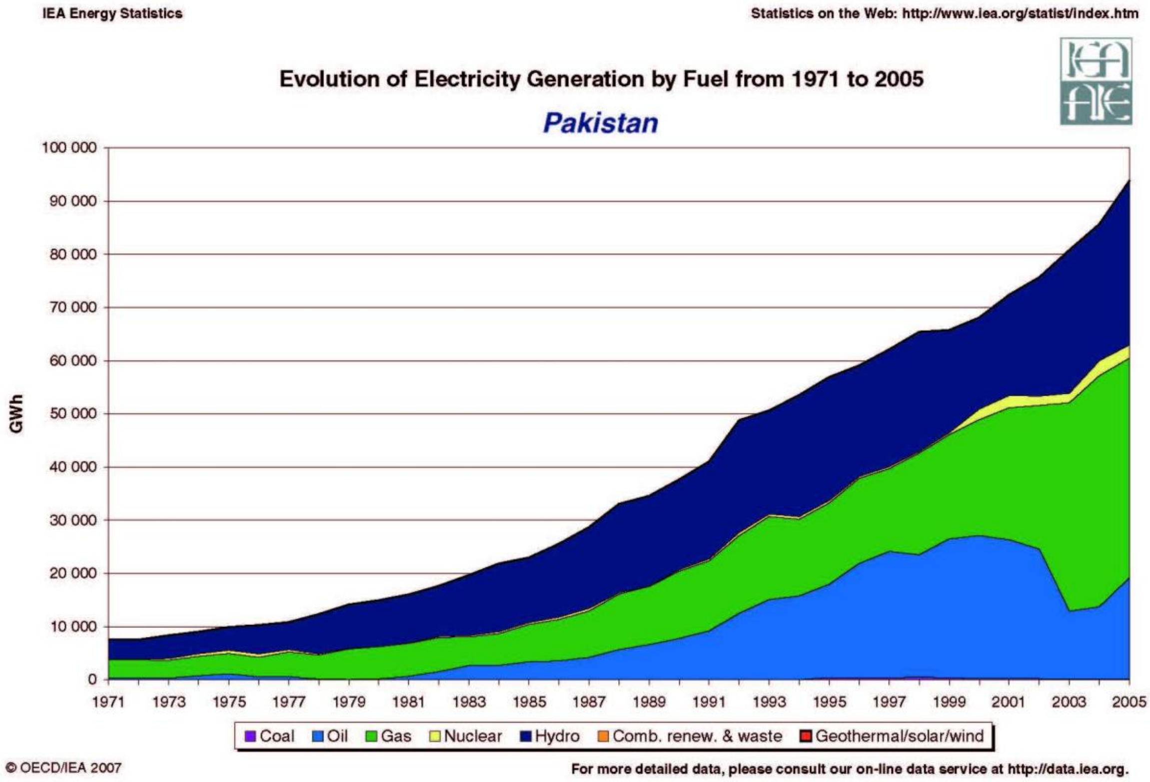


Figure 9 - Pakistan Electricity Generation (Global Energy Network Institute, 2016)

Figure 9 depicts electricity generation for Pakistan up to 2005. It can be easily distinguished that oil, gas and hydro generation have typically constituted to the country's supply, with nuclear generation appearing after the year 2000 and increasing due to future plans of expanding nuclear generation. There is an expected increase in national demand, and due to the current dependence on oil and gas this will follow with an increase in production of carbon emissions. Simultaneously, this will follow with a decrease in oil and gas supply due to finite reserves diminishing resulting in a lack of energy security. This could lead to more blackouts and an incredibly unreliable electricity supply throughout the country. If renewables were implemented for electricity generation within microgrids especially in rural areas, it could potentially decrease the amount of carbon emissions produced, increase security of supply for rural residents and reduce pressure on the national grid in the foreseeable future.

As mentioned before, the Indus River runs through the country and results in multiple other rivers. However, there a numerous other renewable sources which could be utilised such as solar energy, wind energy and biomass combustion.

Due to the vast area covered by Pakistan, and the variety in terrain, it was decided to select one particular province for the purposes of this report. Initially the province of Punjab was selected, therefore natural resources were analysed accordingly. Specifically, the villages selected were Chak 111/12L, Chak 112/12L and Chak 113/12L. These three villages are all in close proximity of each other, based in the Punjab province of Pakistan.

4.1 Punjab and Available Renewable Energy Resources

Research into the climate was completed as it was important to assess which renewable technologies could be utilised in the design of an energy system. Additionally, the climate data collected from research will aid in the validation of the data used in the model. The resources analysed were wind, solar, hydro and biomass.

Wind

Average wind speeds were collected for Lahore, located in the north, and Multan, located in the South. Due to lack of available weather stations in rural areas, for this investigation it was assumed that average wind speeds of the two cities could be extrapolated to the rural areas of Punjab, and that the resources extend to the resources of the villages utilised for the case study.

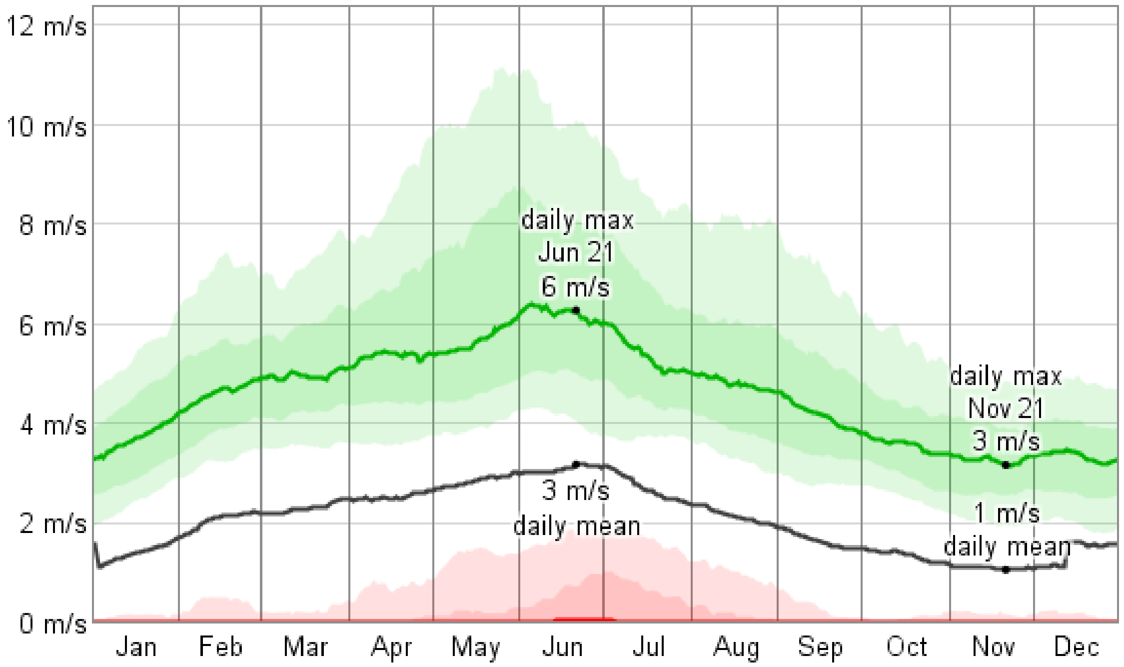


Figure 10 - Average Annual Wind Speeds for Lahore, Punjab (WeatherSpark, 2016)

As seen in Figure 10, the mean wind speeds are relatively low from September to February and minimal speeds are able to read 0 m/s in multiple months throughout the year. A peak in wind speeds is recognised between the months of May through July where wind speeds can reach between 6-11 m/s. The highest average wind speeds are displayed in June at 6 m/s, while the lowest average wind speeds are displayed in November at 1 m/s (moderate to calm breeze).

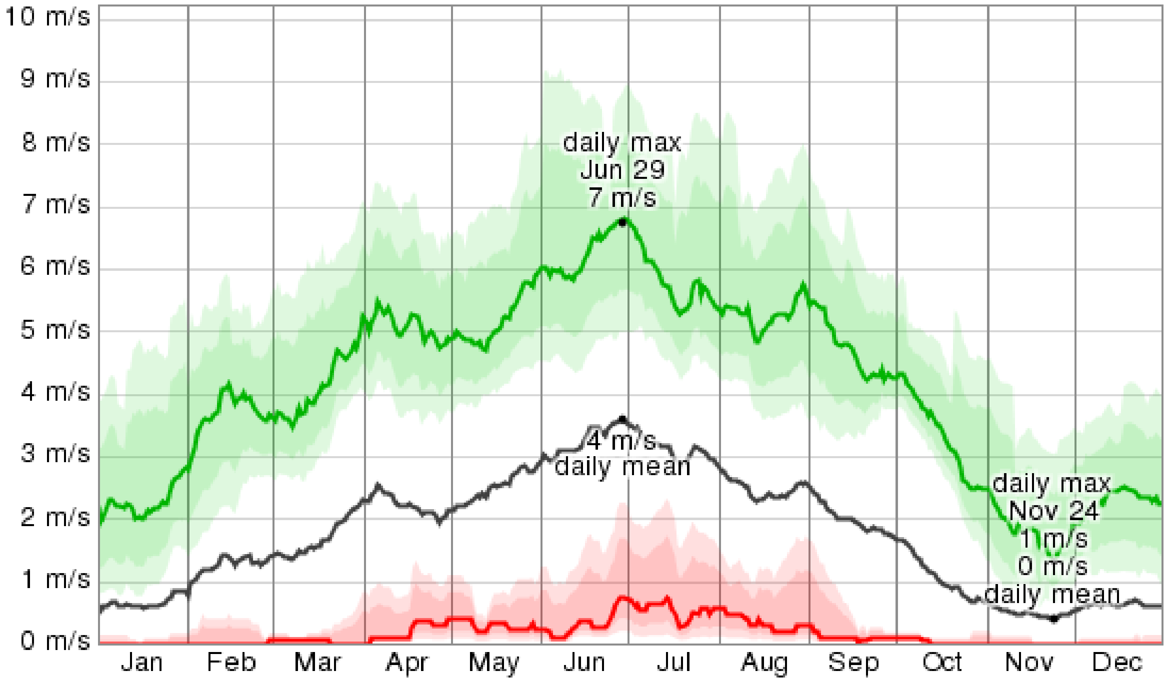


Figure 11 - Average Annual Wind Speeds for Multan, Punjab (WeatherSpark, 2016)

Average annual wind speeds are reflected in Figure 11 for Multan, Punjab. Throughout the year, wind speeds vary from 0-7 m/s with occasional peaks exceeding 9 m/s. The average wind speed is 4 m/s at its highest, and 0 m/s at the lowest.

The two graphs are relatively similar in regards to the highest and lowest average wind speeds, with minimal changes. However, Figure 11 is more volatile and changes drastically compared to Figure 11. The average highest and lowest wind speeds will be averaged and utilised in validation of the wind speeds used for the model in regards to the location of the case study (Chapter 7).

Solar

Dry winter seasons show less solar radiation and so would represent lowest values, with summer displaying the highest. Fall and spring would be intermediate values. Due to the various types of radiation present, annual averages of direct solar radiation – Figure 12, flat plate tilted radiation at latitude – Figure 13, and global horizontal radiation – Figure 14, were collected. Direct solar radiation is utilised in concentrated solar power, while flat plate tilted radiation and global horizontal radiation are utilised in photovoltaics.

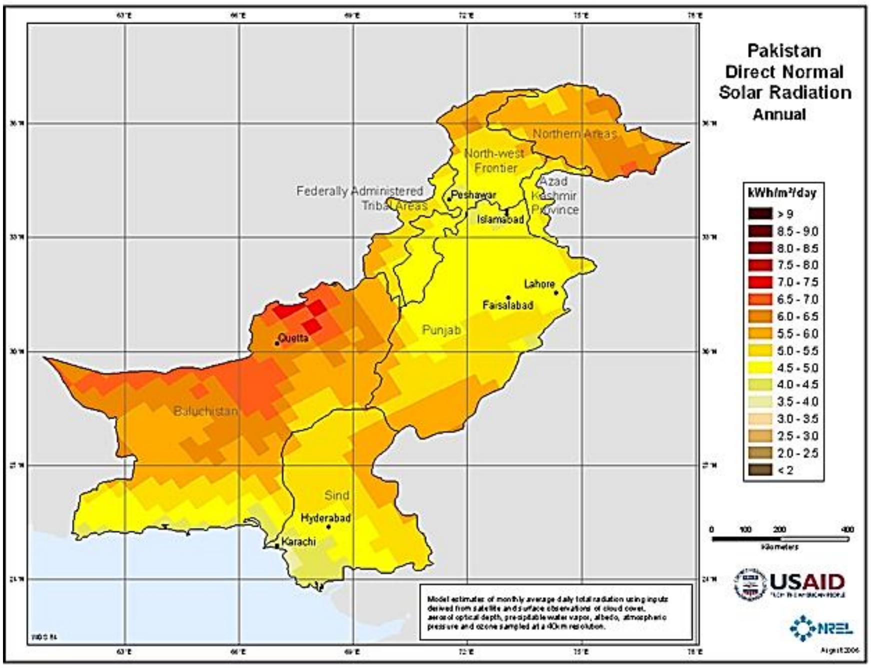


Figure 12 - Direct Normal Solar Radiation Pakistan (Annual) (NREL, 2015)

Annual direct solar radiation is shown in Figure 12. Punjab has relatively lower radiation annually compared to other provinces of Pakistan, with 4.0 kWh/m^2/day at its lowest and 5.5 kWh/m^2/day at its highest. The location of the case study is expected to experience 5.0-5.5 kWh/m^2/day of direct solar radiation annually.

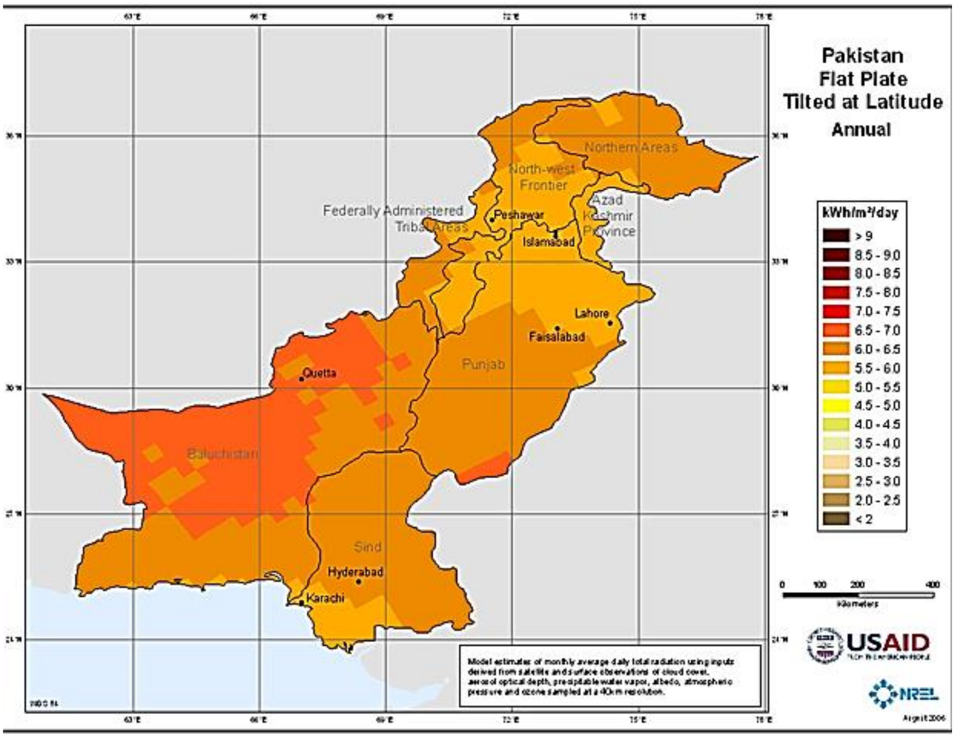


Figure 13 – Annual Radiation Captured Flat Plate Tilted at Latitude (NREL, 2015)

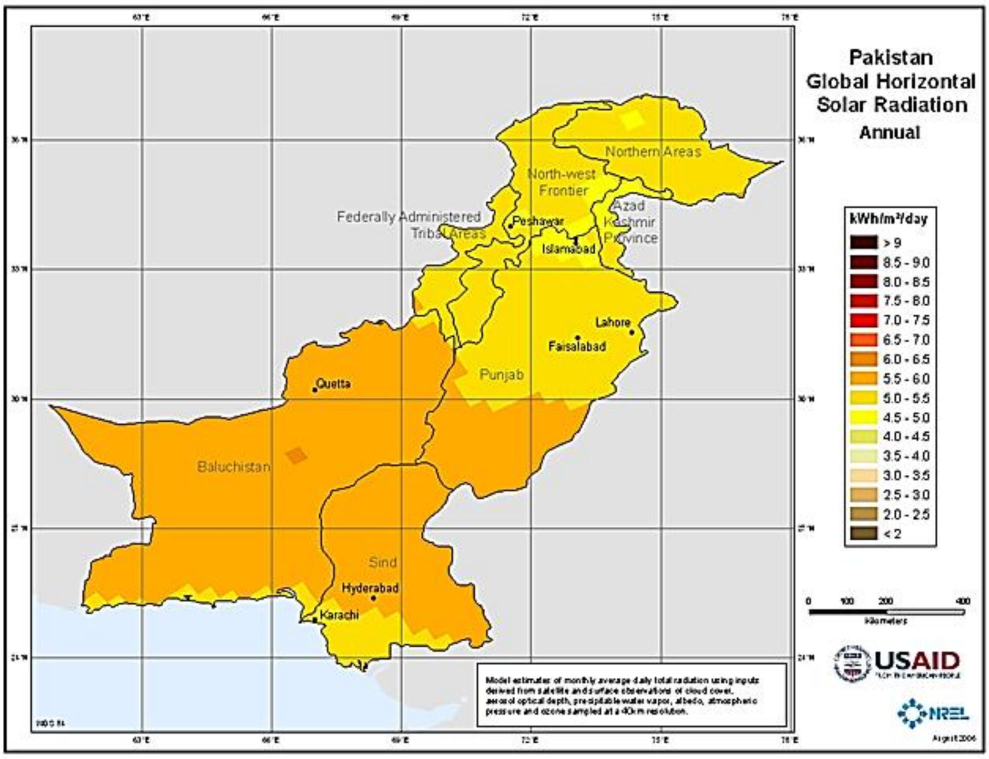


Figure 14 - Annual Global Horizontal Solar Radiation (NREL, 2015)

Figures 13 and 14 reflect the types of radiation which can be utilised by photovoltaic technology. Figure 13 shows the lowest flat plate radiation at latitude in the region of Punjab is 5.5 kWh/m^2/day, and the highest radiation is shown at 7.0 kWh/m^2/day. For the case study the estimated flat plate radiation at latitude is 6.0-6.5 kWh/m^2/day. Figure 14 depicts global horizontal radiation, which varies from 4.5 – 6.0 kWh/m^2/day for the province, but localising for the case study shows an estimation of 5.0-5.5 kWh/m^2/day of horizontal radiance.

Hydro

Pakistan have utilised hydro energy through the form of dams which are dotted throughout the country. Punjab has multiple rivers and canals, which are also used to irrigate agricultural lands.

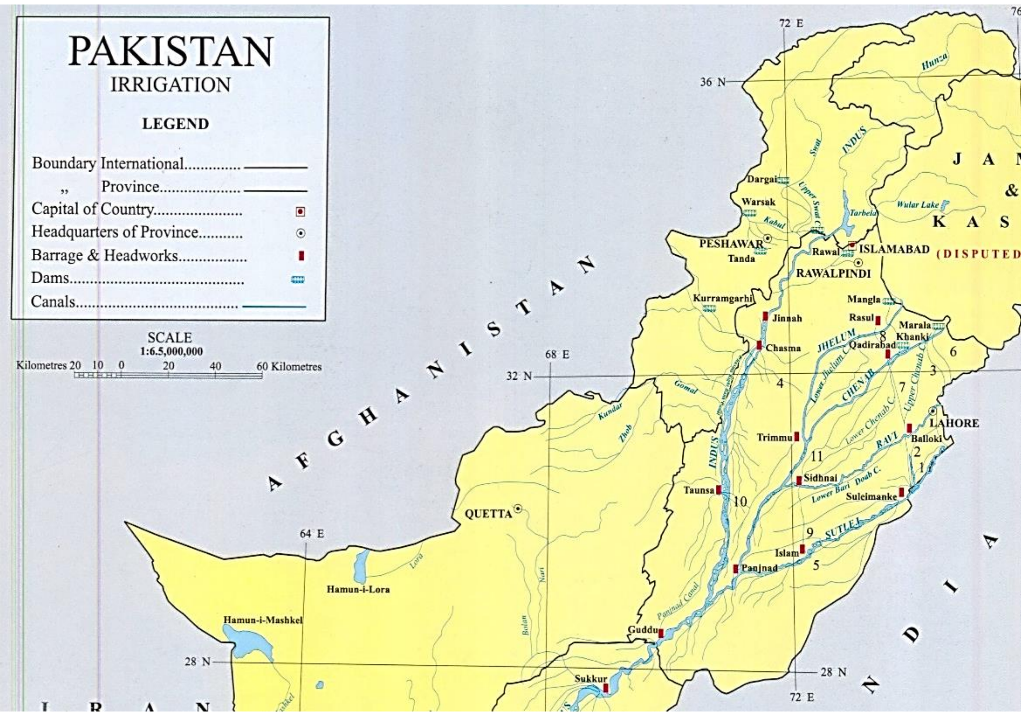


Figure 15 - Rivers and Dams Pakistan (Yousafzai, 2010)

For the rural areas which are near the major rivers, micro-hydro power could be potentially utilised. Figure 15 displays the multiple rivers in Punjab that could provide an effective renewable energy source for a rural energy system for certain locations. However, for this case study, hydro power was not included in the scope and not considered in the model.

Biomass

An excellent resource that could be utilised within the region is biomass, in the form of agricultural waste. Utilising agricultural waste would have inevitable benefits, and could provide a significant portion of electricity to meet the demand.

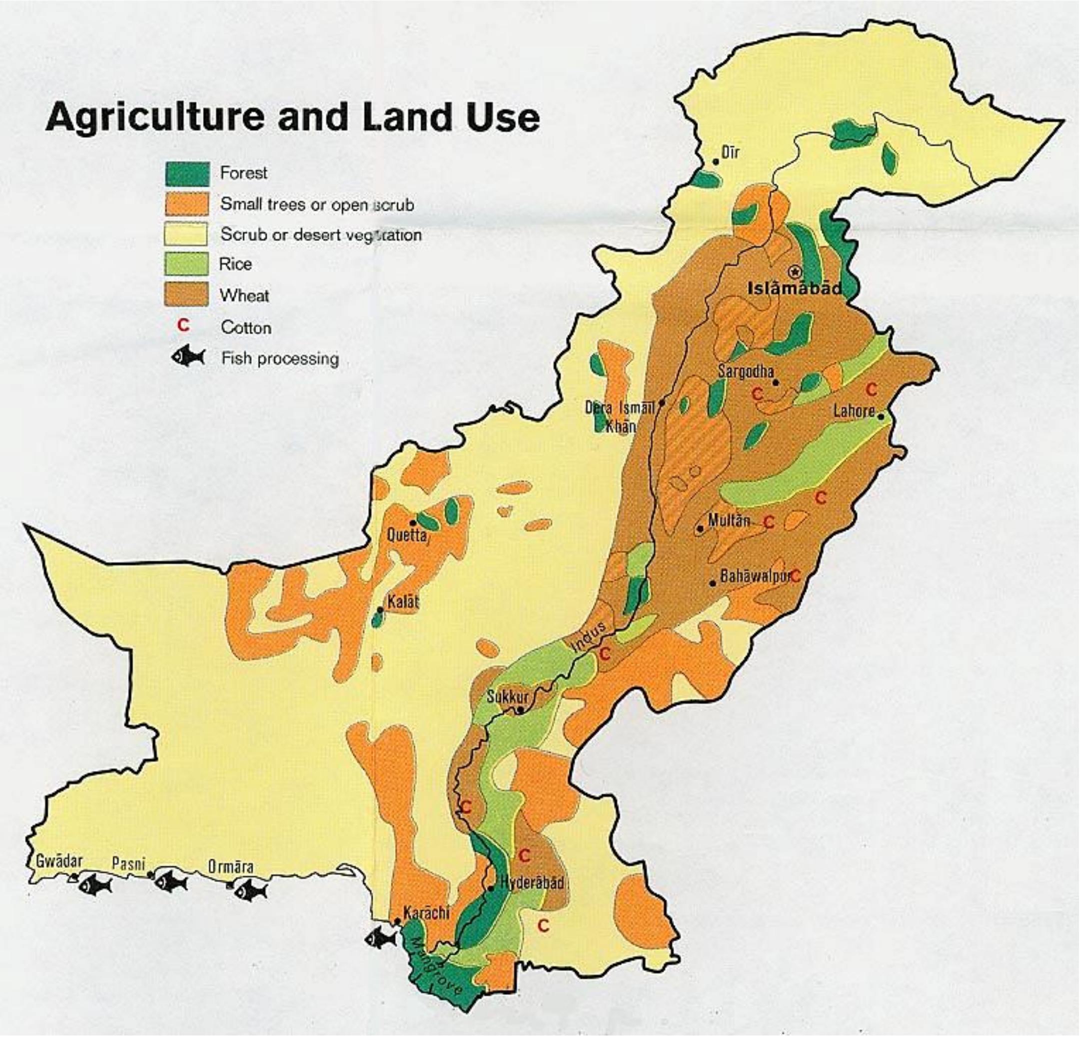


Figure 16 - Agriculture and Land Use for Pakistan (US Central Intelligence Agency, 2014)

As 47% of the total land area is used for agriculture (The World Bank, 2016), with a large proportion of this land located in Punjab – shown in Figure 16. Research conducted has shown that sugarcane, wheat straw, rice husk and maize are the main agricultural wastes, and it could potentially generate 56% of Pakistan's electricity in a sustainable manner as illustrated by Saeed (Saeed, et al., 2015). If agricultural waste could be successfully implemented into an energy system, it would reduce the waste that is sent to landfill drastically, while producing energy in more sustainable fashion in comparison to the burning of diesel and other fossil fuels. Utilising the knowledge from Saeed's research, and through simple calculations it was premeditated that 1 tonne/km^2/day of agricultural waste is produced. However, this was calculated with the assumption that 50% of total agricultural land is based in Punjab. The required land for a biogas generator would depend on the amount of hours it is utilised in a year, and so more discussion regarding the hours of generation (and viability of a biomass generator) is discussed in Chapter 7.

Pakistan has an abundance of resources which can be utilised, in the region of Punjab there are vast renewable resources that can be implemented in a sustainable microgrid for rural communities especially for the case study. A hybrid system consisting of multiple renewable sources would provide an excellent system that could potentially provide resilient, constant and reliable electricity supply to residents.

5. Demand Survey – identifying energy consumption patterns

As information regarding the villages was not readily available, a survey had to be conducted as a method of gathering the necessary data.

The survey was constructed with the aim of collecting information for possible energy efficiency upgrades and to identify energy consumption patterns in the rural village. The survey focused on income levels, types of housings, national grid access and generator access, cooking and lighting demands, air conditioning/heating requirements and use of other appliances such as kitchen or luxury appliances. The results from the survey were used to identify energy consumption patterns and then to construct the demand profile (Chapter 7.1). Pakistan typically has a higher electrification rate compared to other developing countries so residents own and use more electrical appliances. For this survey, 20 different households were approached in one village – Chak 112/12L. The results from this village were assumed to be similar to what would be expected from Chak 111/12L and Chak 113/12L as they are close proximity geographically.

Chapter 5.1 includes the demand survey used and the questions included within. Chapter 5.2 discusses the results of the survey, and concludes with possible improvements that potentially could be implemented to increase energy efficiency.

5.1 Demand Survey Sheet

For each question, a selection of answers is provided in italics on the right hand side, please circle selected answers as appropriate.

1. Housing

Questions	**Answers**
What type of house do you live in?	*Rural Urban Modern*
What materials are used in the structure?	*Cement Concrete Steel Wood Stone Bricks Glass*
Do you have street lights?	*Yes No*
If so, when were they installed?	*6 months ago 1 year ago 2-3 years ago 4-5 years ago 5+ years*
What is your income level?	*Very poor Poor Intermediate Well-off Rich*

2. National Grid Electricity

Questions	**Answers**
Do you have access to electricity from the government/national grid?	*Yes No*
If yes, how often do you get it?	*Daily Weekly Monthly (or less)*
How many hours at a time do you have access to electricity?	*2-4 hrs 4-6 hrs 6-8 hrs 8+ hrs*
Does the electricity cut out frequently, if so how frequently?	*Daily Weekly Monthly (or less)*
When the electricity cuts out, do you still have access to water?	*Yes No*
If no, would you like access to electricity?	*Yes No*

3. Generators

Questions	**Answers**
Do you have access to a generator which provides you with electricity?	*Yes No*
If yes → How frequently do you use the generator?	*Daily Weekly Monthly (or less)*
How long would the generator be switched on for?	*2-4 hrs 4-6 hrs 6-8 hrs 8+ hrs*
What type of fuel does your generator use?	*Diesel Petrol Biofuels (including biomass)*

4. Lighting

Questions	**Answers**
What do you use for lighting in your home?	*Light bulbs kerosene lamps*
If lightbulbs, what type of lightbulbs do you use?	*Incandescent Halogen CFLs LED*
How long would the generator be switched on for?	*2-4 hrs 4-6 hrs 6-8 hrs 8+ hrs*

5. Cooking

Questions	**Answers**
What fuel do you use for cooking?	*Electricity Agricultural waste Firewood Gas*
Where do you get the fuel from? Do you…	*Collect it Buy it*
How often do you cook?	*Daily Every few days Weekly Fortnightly*

6. Air Conditioning

Questions	**Answers**
Do you have an air conditioner in your house?	*Yes No*
If yes, how frequently do you put it on*?*	*Daily Few Days Weekly Fortnightly*
How many hours at a time do you use it for?	*2-4 hrs 4-6 hrs 6-8 hrs 8+ hrs*

7. Heating

Questions	**Answers**
Do you have a heater in your house?	*Yes No*
If yes, how frequently do you put it on*?*	*Daily Few Days Weekly Fortnightly Monthly*
How many hours at a time do you use it for?	*2-4 hrs 4-6 hrs 6-8 hrs 8+ hrs*

8. Kitchen Appliances

Questions	**Answers**
What kind of kitchen appliances do you have in your house?	*Apply the next questions to each appliance.*
How often do you use the appliance?	*Daily Few Days Weekly Fortnightly Monthly*

9. Luxury Appliances

Questions	**Answers**
What kind of kitchen appliances do you have in your house?	*Apply the next questions to each appliance.*
How often do you use the appliance?	*Daily Few Days Weekly Fortnightly Monthly*
For mobile phones and laptops: How often do you need to charge them?	*Daily Few Days Weekly*

5.2 Energy consumption results

The results of the demand survey helped to identify energy consumption patterns for the villages (Chak 111-113/12L), this was used to produce an idea of the energy consumption pattern.

Income level and type of house

As with any community there are bound to be different wealth classes. Those with a lower income will tend to have “rural” types of houses, these tend to be constructed of mud, bricks, cement and concrete with basic interior. Those who are on a higher income level have “urban” style houses which are made of a mix cement, concrete, bricks, wood and stone. Figure 17 depicted below, reflects the proportion of houses that are defined as rural and urban styles in the village. The larger proportion (65%) of houses still possess the rural style, however with increased electricity supply this would decrease due to local economic growth and through obtaining more wealth.

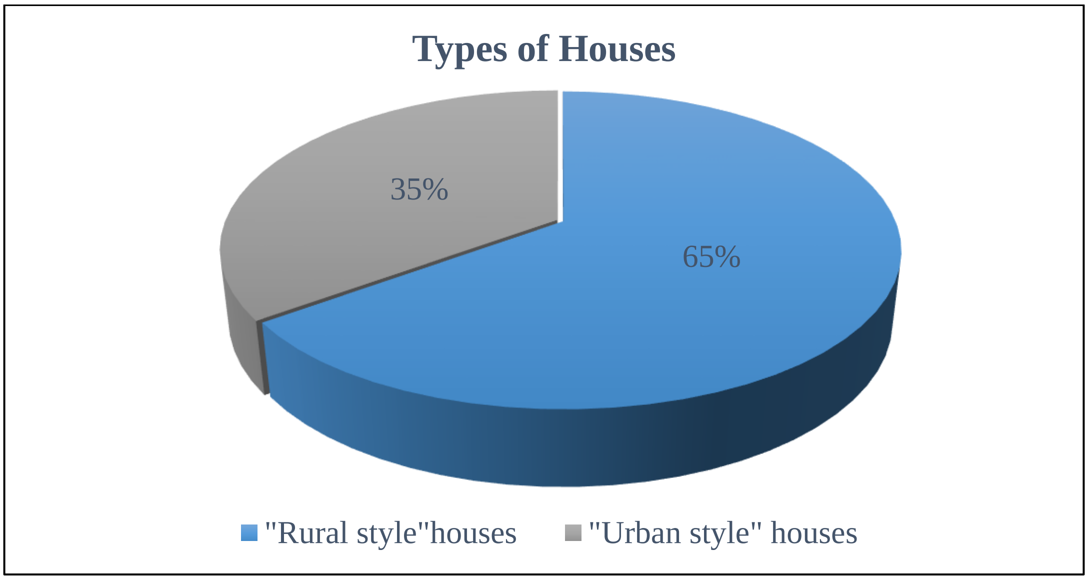


Figure 17 - Proportion of different house styles

Figure 18 reflects the proportion of different income levels in the community. A quarter were identified as very poor, with 30% identifying in the poor region, followed by a quarter identifying in the intermediate region, and a fifth identified as richer (compared to the majority).

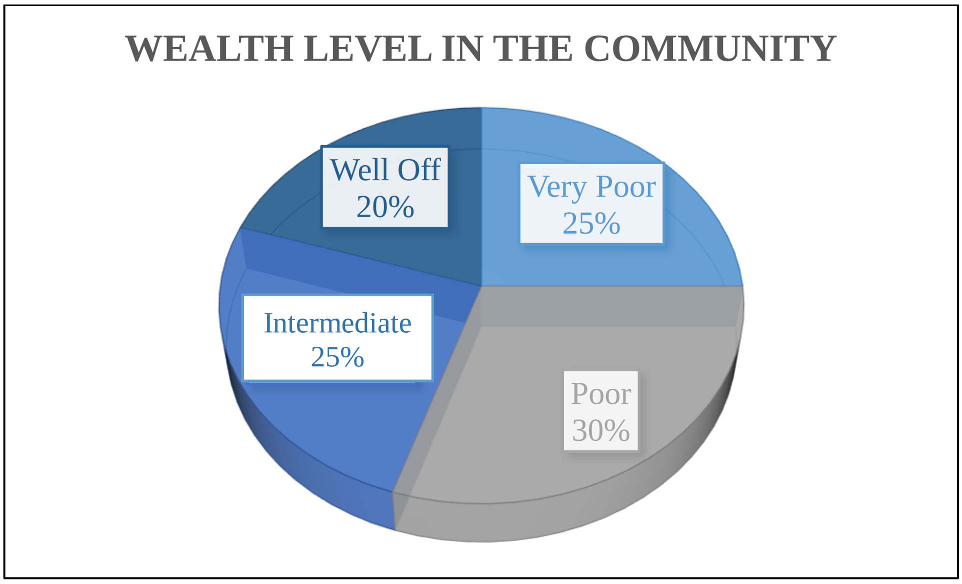


Figure 18 - Wealth Proportion in Community

National grid and generator access

From the 20 households interviewed, 75% of them had direct access to the grid, with the remaining 25% who did not have direct access were able to get secondary access through a neighbour's connection. The supply of electricity from the national grid provided electricity between 2-6 hours at a time, with an average of 3.5 hours of electricity access. The 25% who do not have direct access to electricity would ideally like to have direct access, and it was confirmed that when blackouts did occur, access to water was still available. The results showed that there were no streetlights in the villages.

Many of the residents have access to a diesel generator or a battery generator, which allows to for a supply of electricity when blackouts occur, this was used daily as blackouts occurred daily as highlighted through the results of the survey. Diesel generators were common which those were more well off and reflected 40% of the total generators. The remaining proportion of generators were battery powered, and these were used by lower income level households. The length of time the generators were used ranged from 2-6 hours depending on the availability of grid electricity.

Lighting

Part of the survey was aimed at lighting. Choices of lighting were given, and the three used by the residents are shown in Figure 19 below. The highest proportion used florescent lighting, with halogen the second largest proportion at 44.4%, and kerosene with the lowest utilisation. Lights were used on average for 4 hours a day.

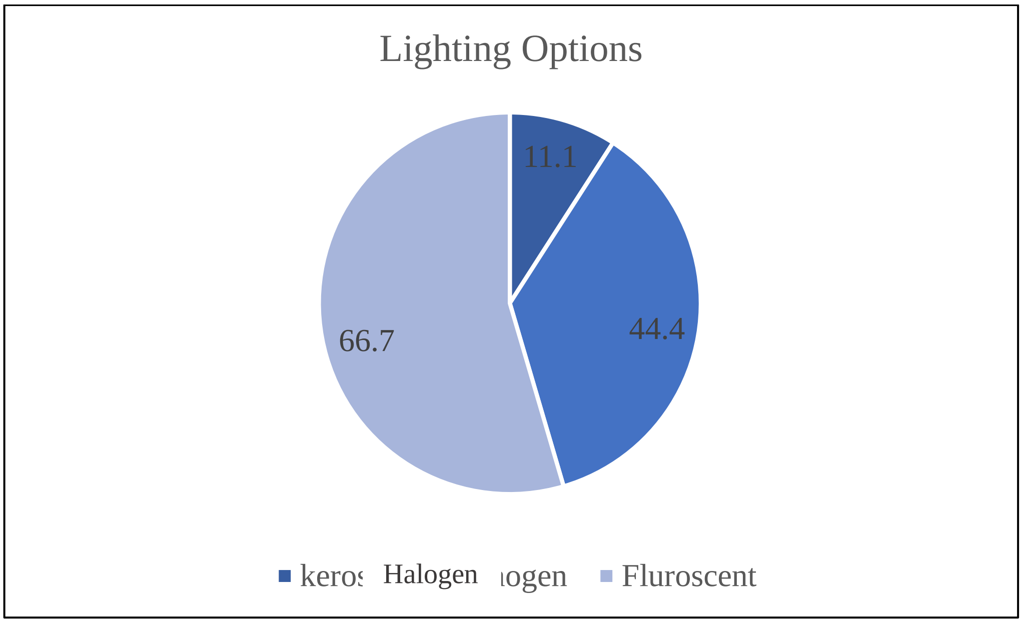


Figure 19 - Lighting Choices

Cooking

Cooking is considered to predominantly be a women's' role in the community and is completed every day. 70% of the residents interviewed were said to have used biomass in cooking, with the remaining 30% using gas. The cooker was used on average 4 hours a day however this is using cookers that were installed over five years ago or low powered cookers. If these were replaced with electric cookers, the time would be halved due to the energy efficiency of new electrical cookers. The installation of electrical cookers would also completely remove the time spent by women collecting and/or buying biomass. 57% of those who used biomass were known to collect it from nearby areas.

Air Conditioning and Heating

All of the households questioned, had access to a dual heater/air conditioner. However, the use of air conditioning is more popular than the use of heating. 60% of residents used air conditioners approximately every day (during the warmer seasons), however during the colder seasons the heater would only be switched on occasionally. On average it can be said that the air conditioner/heater was switched on for approximately 4 hours per day in a household, although heating was switched on for much less time compared to the length of hours the air conditioner was utilised for.

Kitchen and Luxury Appliances

The final section of the survey was used in order to identify other electrical appliances which are used by the local residents which would aid to determine the final energy consumption pattern. Table 1 shows a list of the appliances which appeared commonly on the survey results. Cookers, refrigerators and phone chargers were commonly noted, while the remaining appliances were only owned and used by approximately half of the households.

Table 1 - List of Basic Electrical Appliances and Usage

Appliance	Use
Cooker	2-4 hours a day
Washing Machine	Once a week
Refrigerator	24 hours a day
TV	2 hours a day
Laptop Charger	2-3 hours a day
Phone Charger	3 hours a day

Possible improvements

There are a number of building improvements that can be implemented into these rural households:

- Rural style houses can be upgraded with better building materials, with increased reliability of supply this could be achieved as electricity access is seen to increase economic growth.

- Both styles of houses could benefit by having insulation installed, allowing houses to stay cooler for longer in the warmer seasons and keep buildings warmer during colder seasons. This in turn would reduce the energy consumed for air conditioning and heater.
- Air conditioning and heating systems could be upgraded to systems that are more efficient.
- All lighting options could be replaced with LED bulbs as they consume less energy and have a longer operating life.
- All cooking options could be replaced with electric cookers, which would reduce pollutants produced during combustion of biomass and gas.

Additionally, the survey allowed energy consumption patterns of rural households to be found through data collection and utilised to determine the demand profile – Chapter 7.1.

It should be noted that although a survey was conducted on households in one village with a small sample of 20 household being used due to time constraints. The sample provides a basic demand which can be utilised for the modelling section, however this will not provide an overall picture of the residents of Chak 111-113/12L and is only an estimate for the purpose of this investigation. The demand profile has been included in Chapter 7.1, using the results of the data collection.

6. Software Selection

A number of software options were available which could have been utilised in this investigation. HOMER (Hybrid Optimisation Model for Multiple Energy Resources) software was determined to be best option for this investigation as it is a package which solely focuses on microgrid design and is able to run multiple simulations of various combinations simultaneously. The software simplifies the task of designing microgrid systems (HOMER Energy, 2015), especially for rural communities as it allows for solar, wind and temperature data to be downloaded for any location through respectable sources. HOMER has an added feature called an optimiser which calculates the financial and technical viability combinations. The software also has the added benefit of a sensitivity analysis that reflects the change of one or more variable on the hybrid renewable microgrid design.

Once the software was selected, software familiarisation had to be completed. Additionally, software validation had to be completed to ensure the outputs of the modelling are correct.

6.1 Validation of HOMER

Before utilising the model to design a sustainable energy system for rural communities, the model needed to be validated in order to ensure it functions correctly and produces "realistic" results. The demand for the validation used is a "community" profile with a scaled peak average of 18,202 kWh/day for 1000 households, in order to represent Chaks 11-113/12L (with the same characteristic as depicted in Table 5, Chapter 7.1 also contains a more detailed explanation of the demand used).

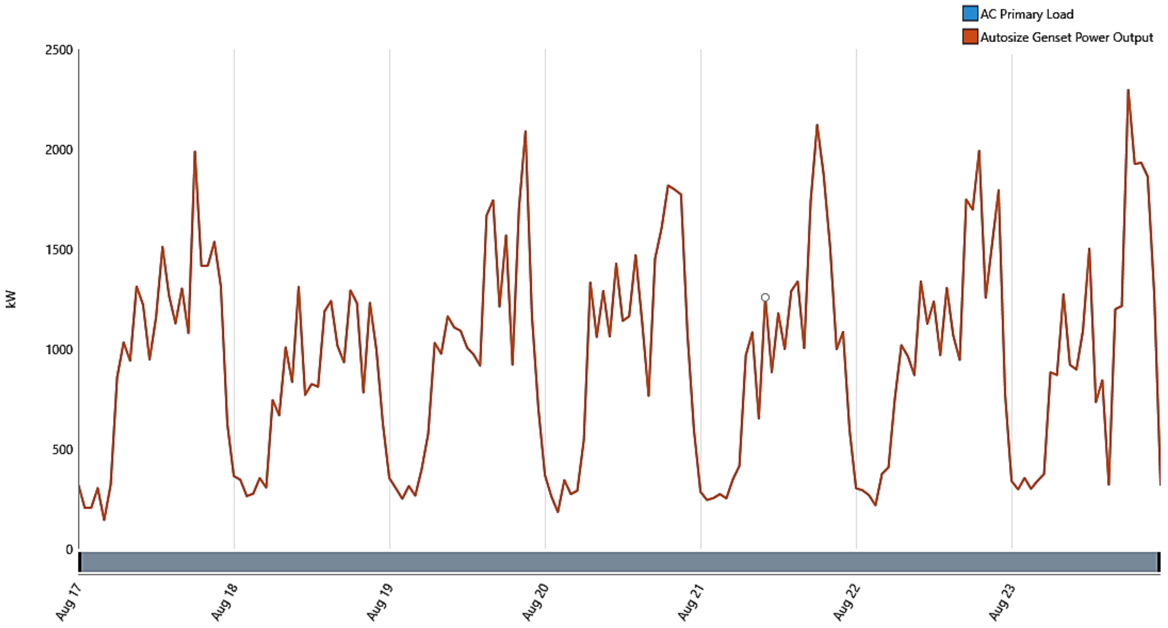


Figure 20 - 1 week demand with an auto-size generator (of 2900 kW)

Initially, a diesel generator was added to the energy system and simulated, this is to reflect the back-up diesel generators used when blackouts occur. Figure 20 shows the generator is functioning on a load following operation, which can be defined as producing just enough power to meet the demand. This mode of operation is what was expected when an energy system only constitutes of a generator to meet the demand.

The next step of validation included downloading the relevant solar resources from NASA Surface Meteorology and Solar Energy Database *(NASA, 2016)* and including a PV array into the simulation. The size of the PV array added was 2000 kW.

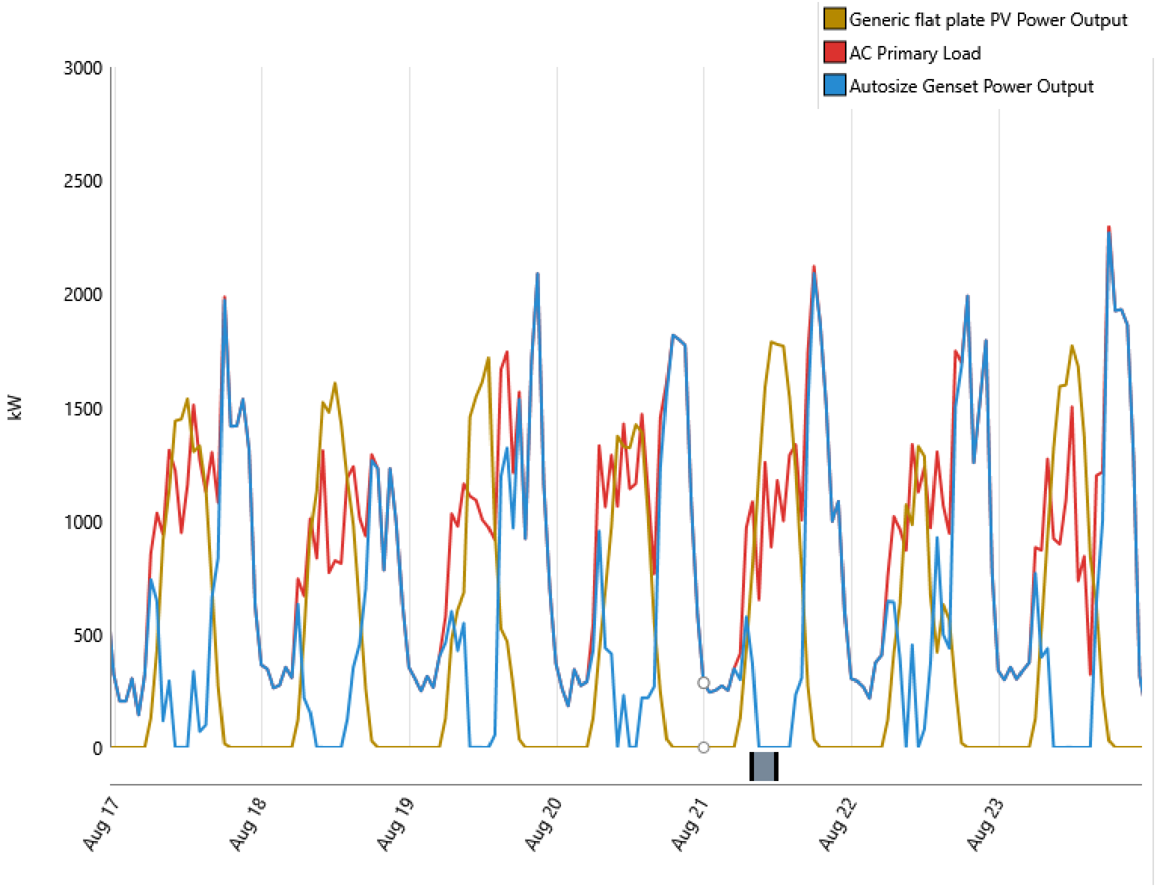


Figure 21- 1 week demand with generator and 2000 kW PV array

The PV output for a week in August is seen in Figure 21. The PV output reaches an approximate peak of 2000 kW, which initially shows good functionality. The annual production of the PV array is 3,471,446 kWh, with a peak of 2000 kW. Therefore:

$$\frac{kWh_{annual}}{kW_{peak}} = \frac{3{,}471{,}446\ kWh}{2000\ kW} = 1700$$

If this is compared to a PV plant in Punjab province of Pakistan *(Phonosolar, 2015)*:

$$\frac{1{,}745{,}000\ kWh}{1{,}250\ kW} = 1400$$

There is a difference between the two ratios, however this could be due to a lower solar radiation compared to the average. As the PV plant is using real results, while the modelled results are using averages, therefore the difference could be due to a lower solar radiation throughout the year compared to average results. Overall, it can be said that the PV array in the HOMER software is working well. Figure 21 also shows the generator is only in operation when the PV output is insufficient to meet the demand, when this occurs, the generator switches on to supply the deficit energy required, as expected in a real life scenario.

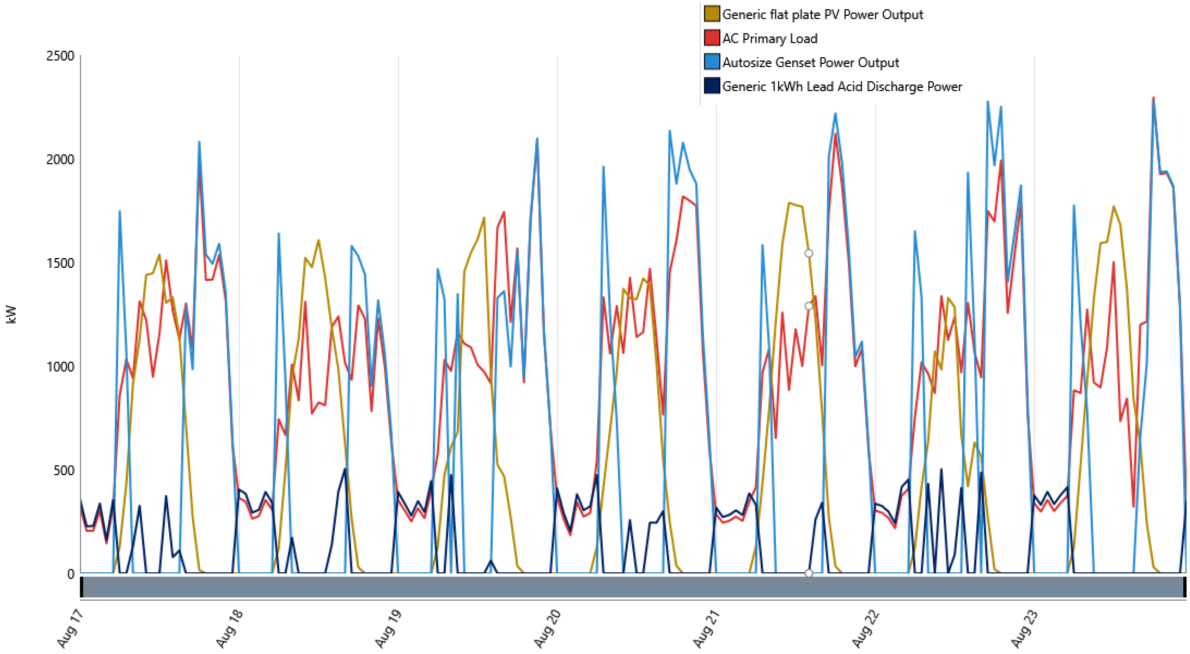


Figure 22 - 1 week demand with generator, PV array and storage

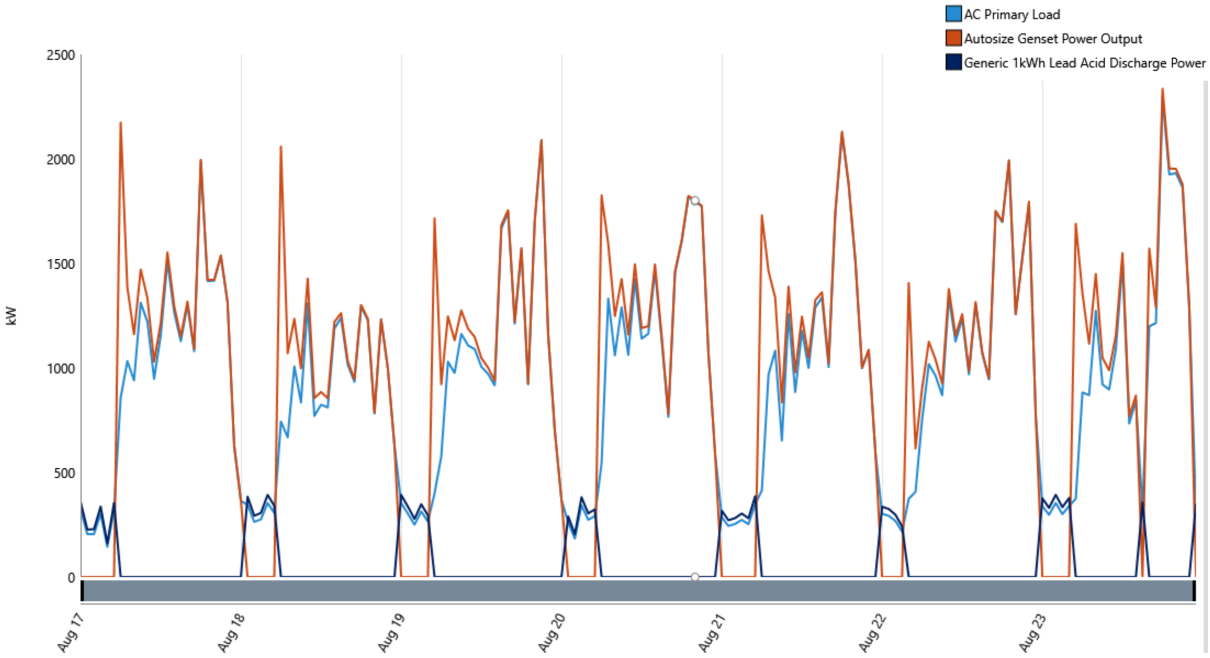


Figure 23- 1 week demand with generator and storage

Figures 22 and 23 show simulation results for a week in August. The results show that the generator only operates to help meet the deficit in supply. However, in Figures 22 and 23, the surplus energy produced from the PV array and generator is stored to be used later. The stored energy is utilised at periods of low demand, such beginning of the day in the early morning as seen in both figures.

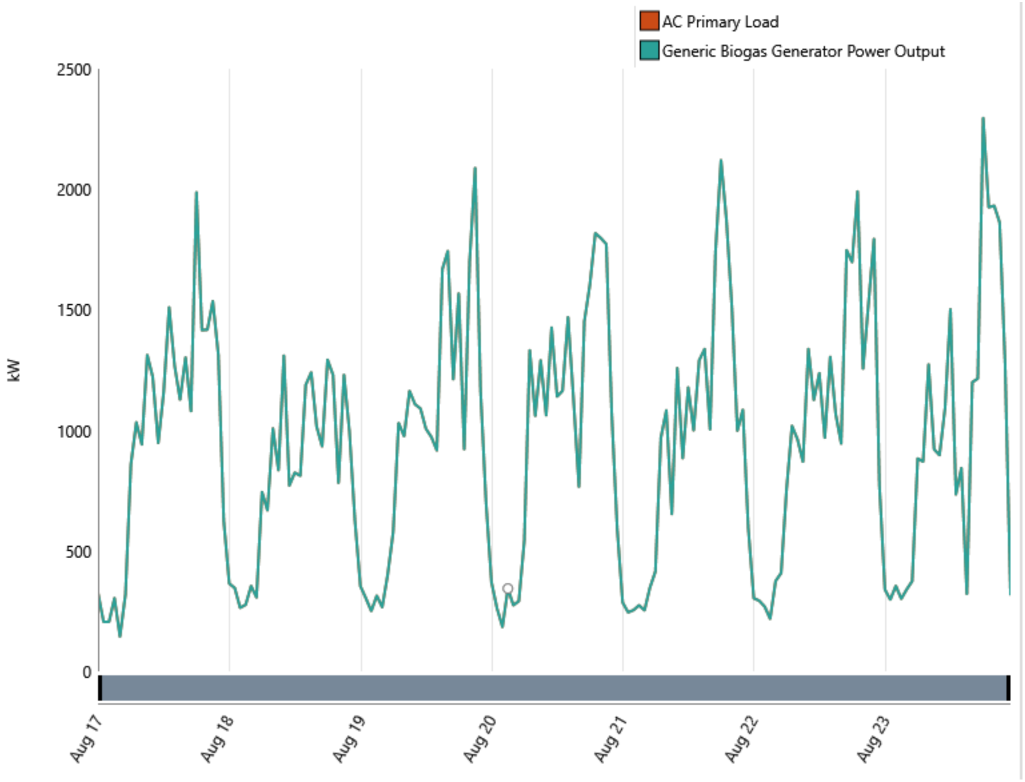


Figure 24- 1 week demand with biogenerator (of 2900 kW)

It was desired that a biogenerator be added to the simulation to make use of agricultural waste. The biogenerator was given 400 tonnes/day of biomass resource for an initial assumption, however it should be noted that this amount could not be sourced sustainably – refer to Chapter 7.5 and Appendix 1. The size of the biogenerator was assumed to be 2900 kW, in order to replace the diesel generator. As seen by Figure 24, the biogenerator standalone energy system works in a load following operation, producing only enough energy to meet the demand as required. This is the desired mode of operation, as no excess energy is being produced, and the load is being met at all times.

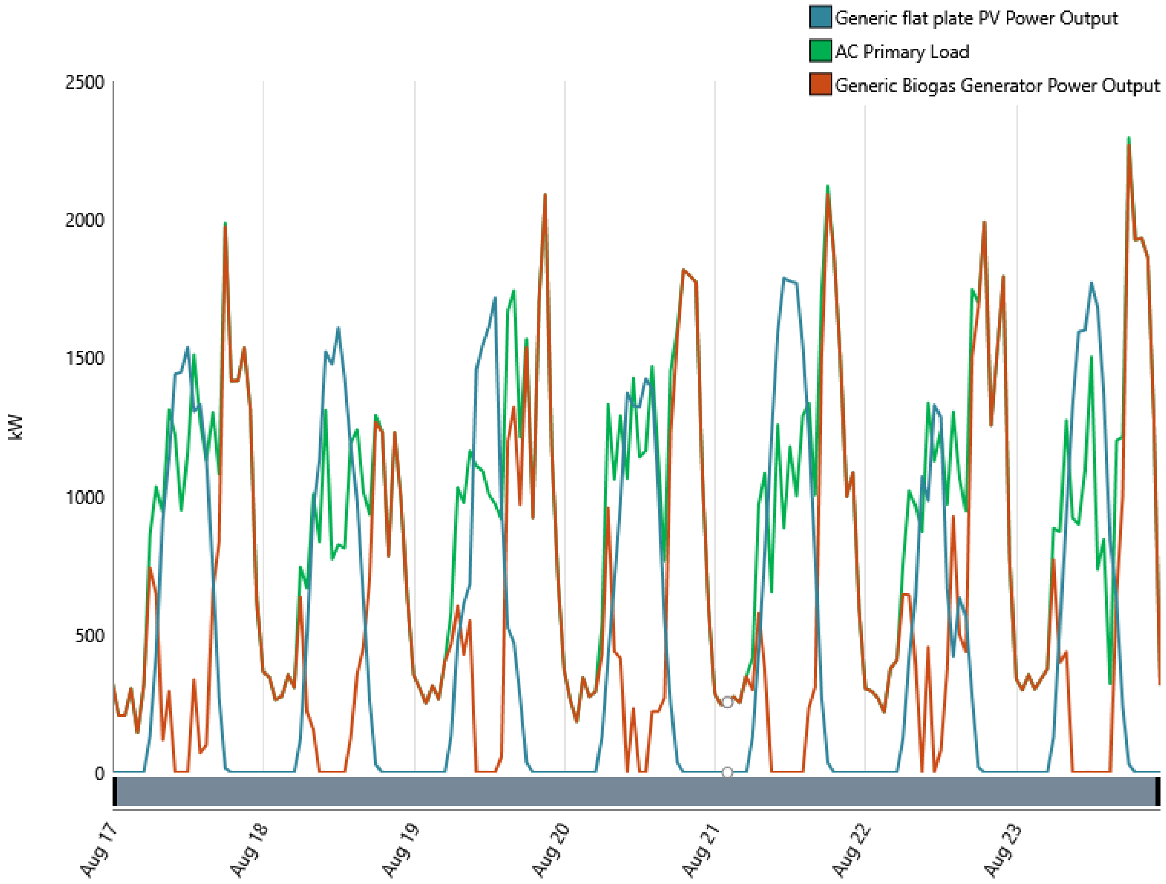


Figure 25 - 1 week demand with biogenerator with PV array

Figure 25 shows the PV output alongside the biogenerator output. It works in the same manner as the generator and PV array, as the biogenerator operates only to make up for any deficit energy between the supply and demand. However, it is seen that in some instances, PV output is excessive and supplies more than the demand. When storage is added to this energy system, the surplus energy produced is stored and used later to meet demands, as seen in Figure 26. If an energy system consists of a biogenerator and storage, the generator operates in a cycle charging mode as seen in Figure 27, as there is no renewable power to store the batteries store surplus energy produced from the biogenerator. This mode allows the generator to operate at peak power for a small period at numerous times throughout the day allowing any excess energy produced is stored into the batteries. This operation method allows more energy to be stored and used later, while if a generator operates in load following mode less surplus is produced as the generator will only produce enough to meet the demand.

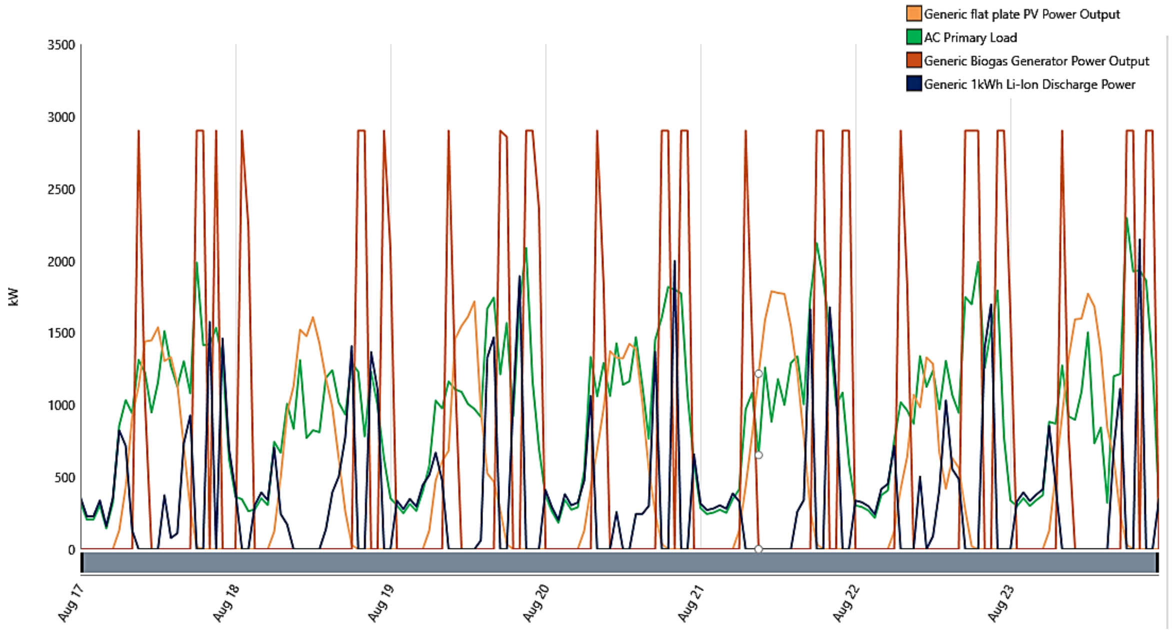


Figure 26- 1 week demand with biogenerator, PV array and storage

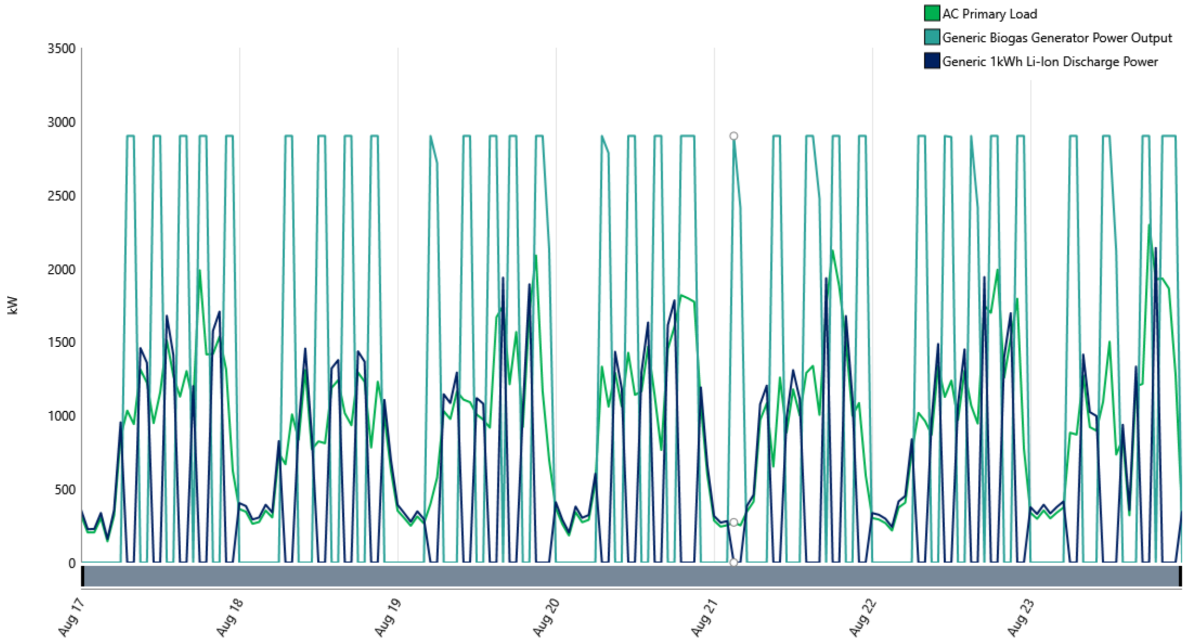


Figure 27- 1 week demand with biogenerator and storage

Overall, the model works as expected and shows results expected of a typical microgrid. Once the model was identified as working correctly, the modelling for the investigation could be completed.

7. Modelling a rural village in Punjab using HOMER

As highlighted before, HOMER was the chosen software to be utilised. Due to the vast size of the Punjab region, a case study was selected. The case study consisted of 3 villages – Chak 111/12L, Chak 112/12L and Chak 113/12L - which is located south of Chichawatni Jungle and the River Ravi, and are located near to the town of Chichawatni. No information was available sizes of the villages, so it was assumed that the villages compromised of 1000 households together. To complete the modelling efficiently, the following aspects needed to be considered:

- Demand profile;
- Solar PV resource;
- Wind resource;
- Diesel generation;
- Biogas generation; and
- Lithium-ion batteries as a form of storage.

Table 2 - Scenario Definitions

Scenario	**Generator**		**Cost**	
	Diesel	Biogas	Present	Future
1	✓		✓	
2	✓			✓
3		✓	✓	
4		✓		✓

The simulations were run in 4 scenarios, as summarised in Table 2:

- Scenario 1 utilised a diesel generator (in order to replace the smaller back up diesel generators used), solar and wind technology at estimations similar to present costs.
- Scenario 2 consisted of a diesel generator, solar and wind technologies however the costs for the renewable technologies were decreased as estimations were based on costs in 2026.
- Scenario 3 replaced the diesel generator with a biogas generator, and used costs estimated to current values for solar and wind technologies.
- Scenario 4 is similar to scenario 3, however the costs for the solar and wind technologies were estimated to costs predicted in 2026.

The scenarios were selected to see how changing certain variables would affect the design of an ideal energy system for rural communities. Scenario 1 was selected as it reflects the current financial situation with regards to diesel and renewable technologies. However, as the financial situation will change in the future, a system which may not be financially viable now could perhaps be viable in 10 years time with lower costs on renewables and increased costs for diesel as a fuel source. For this particular reason, Scenario 2 was designed with future costs for all resource technologies.

With fossil fuel resources depleting, there could potentially be an issue with the sustainable fuel sourcing for diesel, for this reason, it was replaced with a biogas generator in Scenario 3 and 4. However again, the scenario was run on current costs for diesel and renewables, and future expected costs, as what may not be financially viable now will be in the future.

The scenarios are also discussed in more detail in Chapter 7.7.

Calculation of costs for solar and wind technologies

To calculate the future predicted costs of solar and wind energy in 2026, cost curves were used - Figure 2 and Figure 3 from Chapter 2. The year 2026 was selected as percentage changes in prices were calculated between 2016 and 2006 therefore to ensure consistency the percentage change expected was considered over a similar period of 10 years. Solar energy has shown a decrease of 58.3% in the last ten years, with wind energy experiencing a price decrease of 61.5%. Diesel however is expected to continually increase in price, as fossil fuel reserves reduce dramatically. The last 10 years have seen diesel increase in price by 27.7%, as show on Table 3. This is discussed in more detail for individual resources in their related sections.

Table 3 - Percentage change in Price for Scenario 2

Technology	Percentage change
Solar	-58.3%
Wind	- 61.5%
Diesel	+27.7 %

The demand profile was first calculated, as the wind and solar resources were downloaded from NASA Surface Meteorology and Solar Energy Database (NASA, 2016). The generators and batteries information was considered later on.

7.1 Demand Profile

The demand profile had to be determined prior to the running the simulations on HOMER. Using the survey, information regarding the daily use of electrical appliances was found in hours of usage. The hours of usage were then multiplied by the rated power in order to calculate the daily demand (in kWh/Day).

Table 4 - Daily Demand Profile per Typical Household

Items	Rated Power (W)	Daily Use (Hrs)	kWh/Day
Lights (LED) x 5	25	4	0.1
Cooker	1500	3	4.5
Air Conditioning (x3)	2000	4	8
Washing Machine	4000	0.25	1
Refrigerator	180	24	4.32
TV	30	3	0.09
Laptop	60	2.5	0.15
Phone Charger (4)	16	3	0.048
Total			18.2

The demand shown in Table 4 is the typical demand for a household. The following assumptions were made to aid with calculating the demand. As households in rural areas differ largely in size, it was assumed that each household had an average of five members. Households also differ largely in income, and so access to certain electrical appliances would differ between the households. It is assumed that each house had access, or would have access to these basic electrical appliances (listed in Table 1) in the near future.

Table 5- Load Characteristics

Metric	Value
Average kWh/day	18,200
Average kW	758.42
Peak kW	257.7
Load Factor	0.3

A “community” demand profile was selected within HOMER, with an annual demand of 18,200 kWh/day. This load was determined by taking the total demand per household a scaling it by 1000, for the number of households. The type of load selected was alternating current (AC) and had the characteristics reflected in Table 5. It is a common trend for less demand in the early hours of the morning as many occupants would be asleep, the highest demand is seen in the evenings as many of the residents would be at school, work or completing their household tasks during this time, and return in the evening utilising appliances such as TVs, laptops and lighting when required.

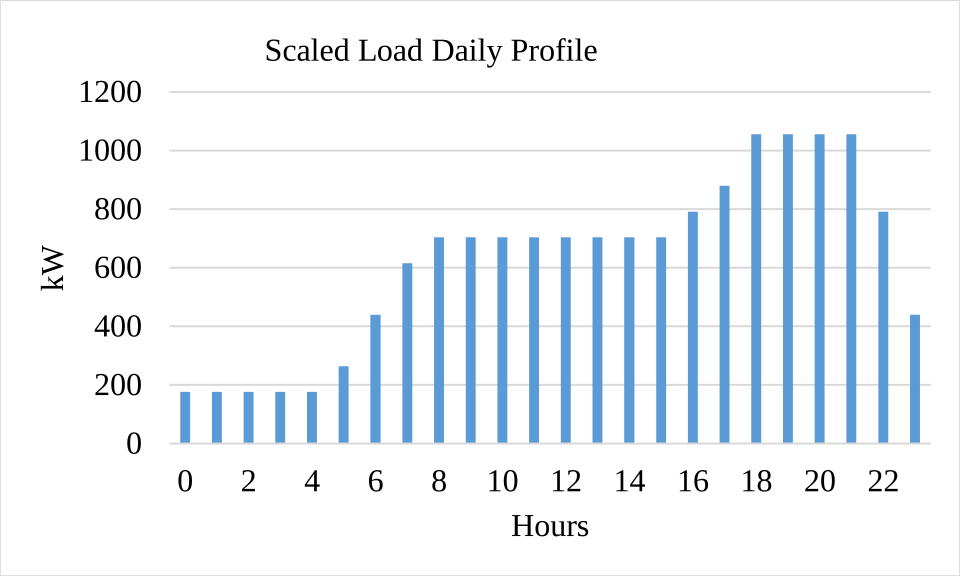


Figure 28 - Average Daily Profile

The demand profile was constructed, and the next step required the consideration of renewable resources.

7.2 Solar PV

Punjab has a high solar resource which can be potentially utilised through photovoltaic technology. HOMER has many options for various types of photovoltaic panels. The monthly average daily radiation and clearness index was taken from NASA Surface Meteorology and Solar Energy Database (NASA, 2016), and is reflected in Figure 29.

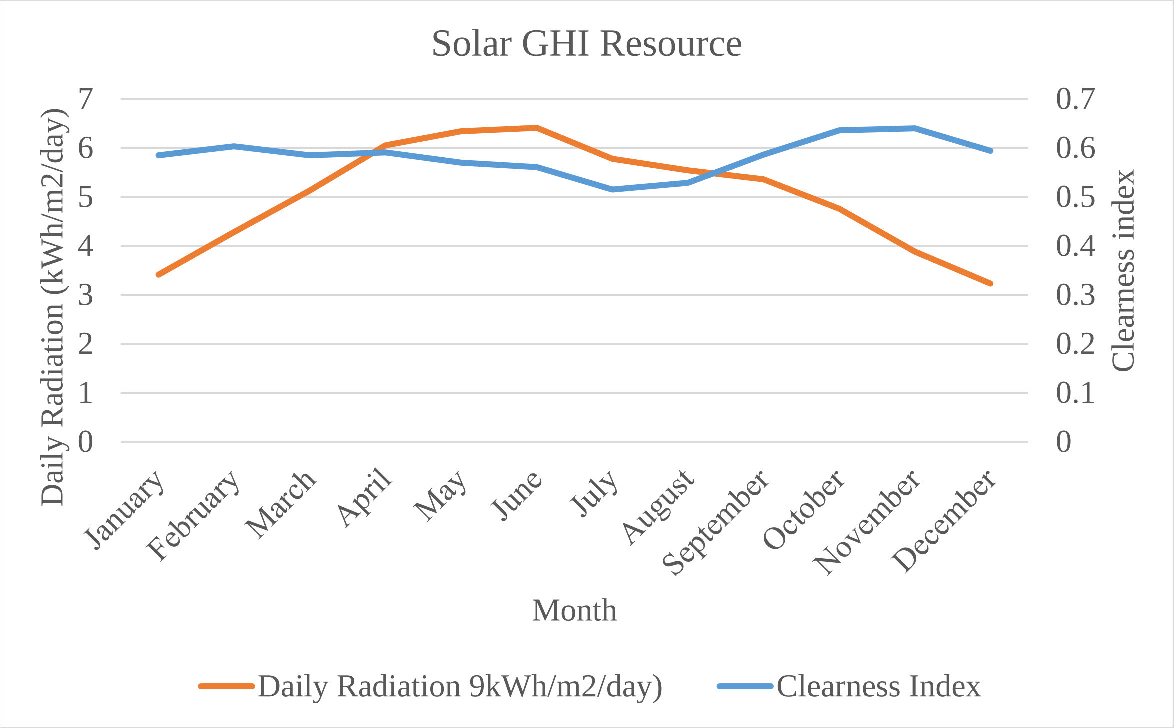


Figure 29 - Solar GHI Resource (HOMER)

The type of panel selected for the simulation was a generic flat plate PV panel, with the characteristics shown in Table 6. The future cost is a predicted decrease in cost, which has been calculated from the decrease in last 10 years and assumed that there will be a similar percentage k. As technology advances, the price will decrease. This has been the trend for the last two decades and is expected to continue into the future.

Table 6 - Generic flat plate PV characteristics

Characteristic	Present	Future
Capacity (kW)	1	1
Capital ($)	3,000	1,250
Replacement ($)	3,000	1,250
O&M ($)	10	4.16
Average Panel Efficiency (%)	16	16

Validation of solar resource

The climate taken from NASA Surface Meteorology and Solar Energy Database (NASA, 2016), is similar to the researched climate information collected. Figure 29 shows similar values of radiation for all of the months apart from January, which is lower. However, the information collected does not show individual months of radiation but reflects an annual average. The month of January taken from the database could still be applicable, as during the winter months, there is generally less solar radiation.

The next renewable resource considered for the modelling was wind resource.

7.3 Wind

The turbine selected from the options provided, was a Northern Power NPS100C-21 wind turbine due to its reliability and its optimised design for the highest annual energy production (Northern Power Systems, 2016). The turbine's characteristics are shown in Table 7. The future cost has been calculated in the same manner as it was for solar photovoltaic.

Table 7- Characteristics for NPS100C-21 Wind Turbine

Characteristic	Present	Future
Rated Capacity (kW)	100	100
Capital ($)	350,000	215,250
Replacement ($)	350,000	215,250
O&M Costs ($)	3,500	2,153

HOMER has a large selection of wind turbines which could be utilised in the model. Initially simulations were run using a generic 1 kW, 500 kW, and 1.5 MW turbine. Using the optimiser it was easily seen as that 1 kW was insufficient, while the others were too large. For this reason, a turbine of 100 kW was selected. The power curve for the NPS100C-21 turbine is displayed in Figure 30. The turbine does not start to produce power until 2.5 m/s where it increases and reaches a steady power output at 15 m/s. Other turbines were also looked at, however many required a higher wind speed to make wind more viable.

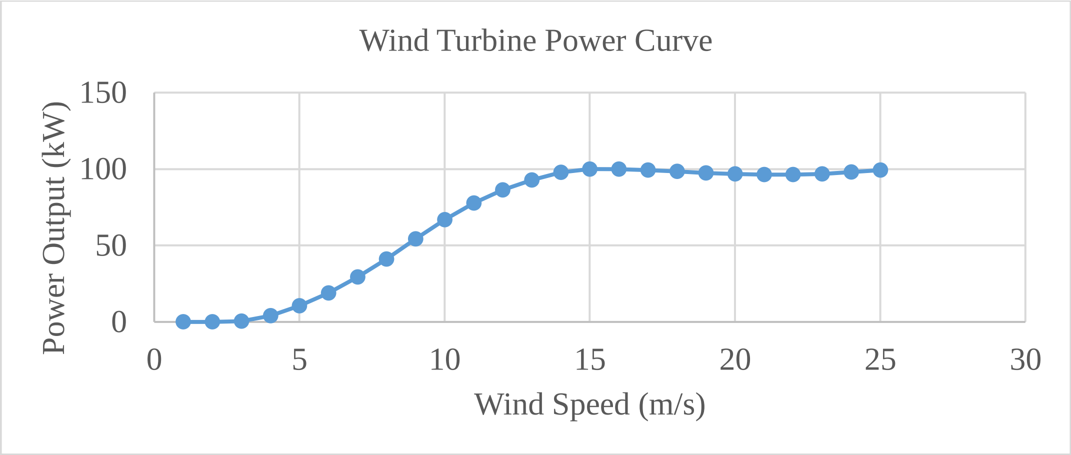


Figure 30 - Wind Power Curve for NPS100C-21 turbine

The average wind speeds will are lowest in October and November, where the wind turbine will produce the least amount of power, as seen in Table 8. Wind resource was downloaded using the NASA Surface Meteorology and Solar Energy Database *(NASA, 2016).*

Table 4 - Average Monthly Wind Speeds at hub height (HOMER)

Month	Average (m/s)
January	2.82
February	3.28
March	3.65
April	3.89
May	4.47
June	4.92
July	4.36
August	3.57
September	3.18
October	2.38
November	2.27
December	2.51

Validation of wind resource

The values for the average wind speed taken from NASA are within the ranges of the mean and max values for wind speeds that were collected through Weatherspark. However, the graphs from Weatherspark only had values for two cities based in North and South of the Punjab province, while values taken from NASA were based on the location of the three villages used in the case study. Considering this, there will be expected slight differences in the average wind speed, and so it can be justified.

The next aspect of the modelling had to consider diesel generation, as this was used in Scenarios 1 and 2.

7.4 Diesel Generator

Diesel generation was considered as the residents use back up diesel generators regularly. The smaller diesel generators could be replaced with a larger generator that could potentially reduce costs and increase reliability.

A diesel generator was added to the initial simulation with the characteristics displayed in Table 9. To ascertain the full effect of the lowered predicted costs for the renewable energy technologies in the future, simultaneously the price of diesel would increase due to reduction of finite resources. The "future" simulation had a diesel price of $1.91/litre, while the "present" cost simulation had a variety of diesel prices to conduct a sensitivity analysis.

Table 9 - Diesel Generator Characteristics

Characteristic	Value
Capacity (kW)	1
Capital ($)	500
Replacement ($)	500
O&M ($)	0.03
Fuel Cost Present ($/L)	Various
Fuel Cost ($/L)	1.91

Although diesel generation was considered for 2 scenarios, there was an emphasis to promote renewable energy generation and reduce reliance on fossil fuels. For this reason, biogas generation was considered as a possible replacement for diesel generation due to the potential of agricultural waste that could be utilised as discussed in the next chapter.

7.5 Biogas Generator

As Punjab has a large agricultural industry, there was potential for a biogas generator to be added to the energy system. Although the biogas generator is more expensive, it could potentially produce a 100% 'renewable' generation which would reduce reliance on fossil fuels and decrease carbon emissions released into the atmosphere. The characteristics of the biogas generator is described in Table 10.

Table 10 - Biogas Generator Characteristics

Characteristic	Value
Capacity (kW)	1
Capital ($)	5,000
Replacement ($)	1,250
O&M ($)	0.10
Fuel Cost($/tonne)	120-240

For the model, it was assumed that there would be more than sufficient volumes of agricultural waste, so a second assumption was assumed of 250 tonnes/day for the modelling of the scenarios. This was based on the fuel curve to generate enough power to replace the diesel generator, which equates to 6000 kg per hour, and for a day equates to 144 tonnes per day, and so a higher value was chosen to ensure enough resource was available to complete the model. However, using statistics (World Bank, 2013) and research conducted from Saeed (Saeed, et al., 2015), the agricultural waste produced was averaged to be 1 tonne/km^2/day. An approximate area of land was selected surrounding the 3 villages (Chaks 111-113/12L) and using Google Earth Pro presented an area of 17.26 km^2.

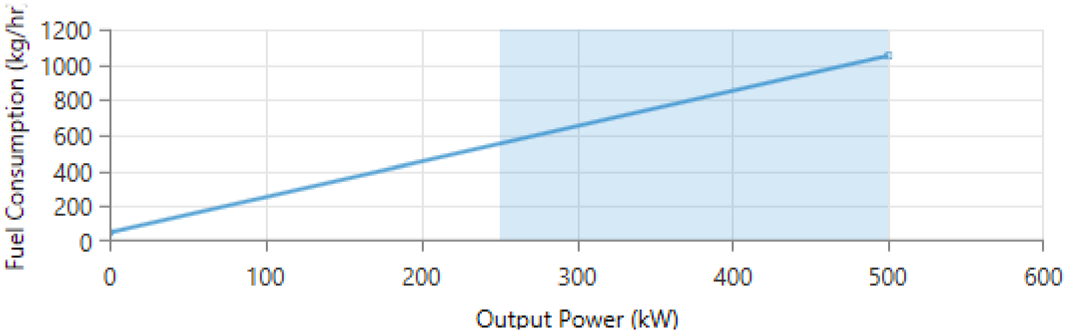


Figure 31 - Biogas Generator Fuel Curve

Considering these figures and using a fuel curve – Figure 31 – within HOMER, more calculations were completed and the result showed that this piece of land would equate to 1050 hours of sustainable operation for a biogas generator per year. If the generator operates for longer than 1050 hours, more biomass would need to be sourced. The calculations for the viable operating hours for the biogas generator are in Appendix 1.

For a microgrid to have high renewable generation and remain stable, energy storage needs to be added. For this case study, lithium-ion batteries were considered.

7.6 Lithium-ion Battery

The technology selected for energy storage was a Li-ion battery. Inclusion of an energy storage technology is important as the microgrid design is desired as it will increase stability of the system when large portions of renewable intermittent energy is produced. The Li-ion battery characteristics that were included in the simulation are shown in Table 11, which were taken within HOMER.

Table 11 - Li-Ion Battery Characteristics

Characteristic	**Value**
Quantity	1
Capital ($)	600
Replacement ($)	480
O&M ($)	10
Nominal Capacity (kWh)	1
Roundtrip efficiency (%)	90

7.7 Scenarios

HOMER allows the input of variables, and use of an optimiser to find the optimum design of a microgrid for rural application. A summary of the scenarios, which were investigated, are listed in Table 2. This chapter will discuss the scenarios in more detail.

For each of the scenarios, optimisation was completed by varying the renewable and non-renewable generation and the capacity of storage. The scenarios also differed with costs, and different configurations of generation in order to identify an ideal energy system. The ideal energy system should meet the following criteria:

- Provide sufficient secure electricity to meet demand to the fullest extent;
- Be financially viable;
- Have increased renewable generation; and
- Have minimum carbon emission produced.

With the criteria in mind, the scenarios were designed to identify the ideal energy system for the case study of the three villages – Chak 111/12L, Chak 112/12L and Chak 113/12L – in the Punjab province. The modelling scenarios aimed at seeing how lower renewables with increased diesel would affect an ideal energy system for rural application. It also focused on having sustainable generation and so in the final two scenarios, the diesel generator was replaced with a biogas generator.

Scenario 1

This scenario includes renewable energy resources such as wind and solar technologies, with assumptions of costs according to current standards. It also includes Li-ion batteries, a 10,000 kW converter and a diesel generator. A schematic is shown in Figure 32.

The wind speed and diesel price had multiple values, in order to conduct a sensitivity analysis for the following questions:

- What would be the ideal system is wind speed was lower?
- What would be the ideal systems if diesel prices increased?

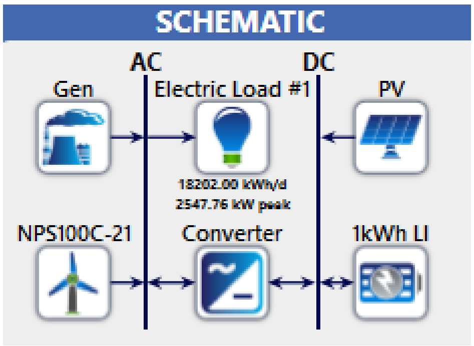


Figure 32 - Schematic of system (Scenario 1 & 2)

Scenario 2

This scenario is similar to scenario 1, with the only difference in the capital, replacement and O&M cost for solar and wind technologies are decreased as this is what is estimated for the year 2026. Diesel fuel prices were increased. This is to replicate future estimated costs. Only the wind speed variable changed to see what effect this would have on the system.

Scenario 3

Scenario 3 replaces the diesel generator with a biogas generator, with all costs of renewable technologies (wind & solar) to be assumptions for present day value – similar to scenario 1. The factors which varied in this scenario were wind speeds and price per tonne of biomass, to see how it affected the design of the optimal system.

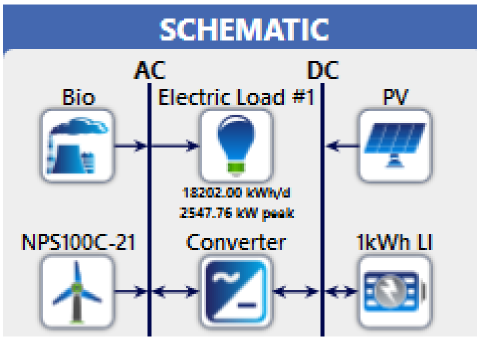


Figure 33 - Schematic of System (Scenario 3 and 4)

Scenario 4

The final scenario is similar to scenario 3, with costs of solar and wind technologies being assumed to meet future value (for the year 2026) of the technologies.

With the scenarios defined, the next aspect of the investigation required the simulations of these scenarios and the results analysed.

8. Results and Discussion

There are many factors that to be taken into account to ascertain a suitable microgrid design. In order to identify an ideal energy system for this investigation, there are four components which need to be met in order for a microgrid system to be deemed suitable. The system:

1. Should be able to meet demands, with minimum unmet load per year;
2. Significant generation should be due to renewable resources – high renewable fraction. It should be noted that the renewable fraction is calculated as the percentage of load met by electricity that is generated through renewable resources;
3. Be financially viable; and
4. Have reduced carbon emissions.

These four objectives were used to identify the most suitable systems in the following results of the various scenarios.

8.1 Scenario 1 Results

Table 12 - Scenario1 Result

Unmet Load (kWh/year)	Ren Frac (%)	CO2 Emissions (kg/year)	COE ($)	NPC ($)	WT	PV (kW)	1 kWh Li	Generator (kW)	Converter (kW)
0.0	28.9	3,402,603	0.36	30,537,780	0	1,991	2,477	2,900	10,000
0.0	29.2	3,385,731	0.36	30,837,580	1	1,974	2,585	2,900	10,000
0.0	0.0	5,440,651	0.41	34,466,110	0	0	2,252	2,900	10,000
0.0	0.0	5,403,561	0.41	34,784,770	1	0	2,133	2,900	10,000
0.0	37.2	3,588,355	0.46	38,813,530	0	2,275	0	2,900	10,000
0.0	37.7	3,564,982	0.46	39,164,100	1	2,275	0	2,900	10,000
278,943.3	100.0	0	0.54	43,575,380	0	6,907	20,154	0	10,000
283,480.4	100.0	0	0.54	43,580,170	1	6,783	20,098	0	10,000

8.2 Scenario 1 Discussion

The initial simulations were completed using a hybrid of renewables and a diesel generator. Exploiting the HOMER Optimiser, the diesel generator is optimally sized. Table 12 shows the results of the systems with the lowest net present costs – which represents the lifetime cost for the system.

In this scenario, wind and PV technology is less established than diesel generation, and so renewables are more expensive. This reflection is brought to light by the results, as six combinations out of the eight have small renewable fractions. These 6 combinations have varying proportions of diesel generation, ranging from 62.8-100%. Although there are 100% renewable systems, these two combinations have a significant unmet load per year when compared to the systems which consider diesel generation.

Autonomy of the energy system is a critical objective to meet, and so the unmet load is an important factor of the system to consider, as it reflects how well the system could be autonomous. Systems which have high unmet load initially could be potentially unstable during operation. It is also important to note that storage is essential in order to take advantage of the power generated from renewables. As the peak supply may not be at the same time of peak demand, and so any surplus energy produced could be stored and used later. This could also increase the renewable fraction as mentioned in the sensitivity analysis (refer to Chapter 9).

In regards to the unmet load, the options which do not meet the first objective are the configurations which have 100% renewable fractions. These two combinations are also the most expensive, and so considered unsuitable for rural application.

The next objective is the renewable fraction. There are two systems that do not feature any renewable generation, and so were considered to be unsustainable in the future due to depleting fossil fuel resources which could potentially lead to increased diesel prices. For this reason, these two systems were also not considered to be suitable for rural application.

This leaves four systems with varying renewable fractions. However, two of these systems do not feature storage. The exclusion of storage is problematic in systems which feature a significant portion of renewable generation due to their intermittent nature. This can lead to high amounts of renewable generation which may exceed demand and could potentially cause instability issues in the system. HOMER includes options which do not feature storage as it models many different combinations, and produces the optimised results based solely on the net present cost of the system. Although HOMER considers the combination suitable – due to net present cost – for this investigation, options which do not feature storage are identified as practically unfeasible.

The two options left have renewable fractions of 28.9% and 29.2%. There is not much difference between the systems apart from one system being a wind-solar-diesel hybrid system and the other being a solar-diesel hybrid system. The next two objectives consider cost and emissions. For these two systems, the carbon emissions and net present cost are not drastically different, so either system could be defined as suitable. Nonetheless, both systems are heavily reliant on diesel generation, and so cannot be considered ideal as it is desired for them to have a higher renewable fraction. The low renewable fractions of these systems are due to wind and solar technologies being expensive in current financial standards, high volumes of renewable generation would be considered financially unviable. The wind resource of the case study location is typically lower, and there is insignificant power output from the wind turbines due to the low wind speeds. HOMER features a wind turbine in the system to be financially viable, it solely bases financial feasibility on the net present cost, and does not consider value for money, however due to the low power output a wind turbine is not suitable for the location of the case study and so should not be featured in the ideal system.

Considering the criteria and analysis of the results, there is no perfect energy system in this scenario. However, the most suitable solution from the available combinations would be a heavily relied upon diesel generation, with 2,600 lithium batteries as storage, and 2,000 kW of PV with a 29.2% renewable fraction. This type of hybrid system has lowest carbon emissions of 3.4 million kg per year, therefore takes full advantage of the energy generated from the PV array. The system is said to be financially viable costing $31 million dollars, one of the substantially cheaper options with zero kWh per year of unmet load.

Ideal system for Scenario 1

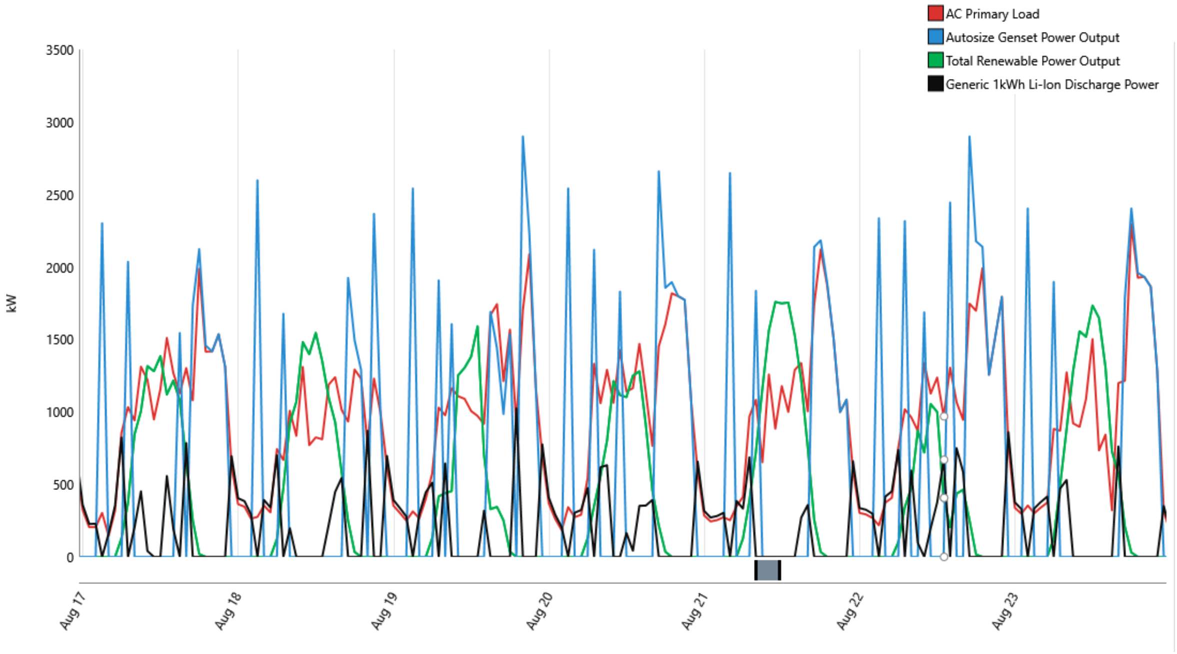


Figure 34 –Suitable solution from configurations, demand and power output from sources

Figure 34 shows the demand for a week in August, with the relevant power outputs for the ideal system generation sources. The generation sources include renewable sources (2000 kW PV array), batteries and generator. The generator operates in the mode of cycle charging. It produces power and peak supply in the early hours of the day, which allow to meet demand and provide surplus energy which is stored to be used later. During the time of the renewable power generation, which is intermittent, the generator does not operate (unless renewable supply is low) as the demand is met through the renewable power generated and the surplus energy stored in the lithium batteries. However, when there is no renewable power output, the generator operates in a load following mode, producing enough electricity to meet the demand with minimal surplus energy.

Although the renewable fraction of this system is typically lower than desired, this could be increased in the future as the costs of renewable technologies are expected to reduce (according to Figure 2 and 3 in Chapter 2). This will be reflected in Scenario 2.

8.3 Scenario 2 Results

Table 13 - Scenario 2 Results

Unmet Load (kWh/year)	Ren Frac (%)	CO2 Emissions (kg/year)	COE ($)	NPC ($)	WT	PV (kW)	1 kWh Li	Generator (kW)	Converter (kW)
0	93.9	368,093	0.43	36,130,310	0	6,684	16,590	2,900	15,000
0	93.2	407,098	0.43	36,229,120	1	6,473	16,002	2,900	15,000
0	47.7	2,943,621	0.66	55,878,770	0	5,830	0	2,900	15,000
0	48.2	2,933,131	0.66	55,929,860	3	5,404	0	2,900	15,000
0	22.0	3,752,633	0.77	65,000,900	64	0	3,046	2,900	15,000
0	0.0	5,317,375	0.86	73,002,130	0	0	1,896	2,900	15,000
275,425	100.0	0	0.39	31,829,820	0	8,888	14,931	0	15,000
281,704	100.0	0	0.39	31,791,990	3	7,336	17,582	0	15,000

8.4 Scenario 2 Discussion

Scenario 2 simulations were run with lower costs for the renewable technologies and a higher fuel price for diesel to replicate future predictions. The results of systems with the lowest net present cost are displayed in Table 13.

Unlike scenario 1 results, the results show considerably higher renewable fractions with zero unmet load per year. Although, the systems which have 100% renewable fractions have a large unmet load between 275,000-282,000 kWh per year, which is not suitable to be implemented into a rural area regardless that these combinations having theoretical zero carbon emissions, and are cheaper at a cost of $32 million.

The configurations which include diesel generators as part of a hybrid diesel-renewable system reflects a significant increase on the proportion of renewable fractions. However, the configurations with renewable fractions of 50% or lower produce amplified carbon emissions – because of the increased reliance and operating hours of the generator.

There are a large number of suitable options, withal considering the criteria mentioned previously. When considering the unmet load and autonomy of the system, the systems which are solely 100% renewable fractions are unsuitable and could not be considered. The next objective is the renewable fraction. The system with zero renewable generation cannot be considered for the ideal system because of unsustainable future for diesel due to reduced fossil fuel reserves. This system would also be unsuitable as it has no storage facility, in addition to the 22% renewable fraction system. Considering the remaining criteria, the two suitable options are the systems with 93.2% and 93.9% renewable fractions. However, again one system contains a wind turbine. Wind turbines are not value for money when considering their low power output, and the remaining system has the lowest costs and emissions, therefore is the best option.

Ideal system for Scenario 2

The configuration of the ideal system for scenario 2 is listed in Table 14. The system consists of PV panels, batteries and a diesel generator. It has zero unmet load, produces 370,000 kg of carbon emissions in a year – which is significantly lower compared to the ideal system in scenario 1. The system has a renewable fraction of 93.9% and has a net present cost of $36.1 million. This system is solely a PV-diesel hybrid system, with batteries as a source for energy storage. Although it is relatively costly when compared to the 100% renewable systems, it provides a reliable electricity supply due to the small proportion of diesel generation. If this system were to be priced with present costs as in scenario 1, it would equate to $48 million, however this system has a higher cost of energy when compared to the system selected in scenario 1, ultimately due to increased PV and battery capacity.

Table 14 – Viable System for Scenario 2 (PV-diesel-storage hybrid)

Unmet Load (kWy/year)	Renewable Frac (%)	CO2 (kg/yr)	COE ($)	Cost/NPC ($)	WT (no)	PV (kW)	1 kWh Li
0	93.9	368,093	0.43	36,130,310	0	6,684	16,590

Figure 35 displays the power output and demand for the system displayed in Table 14 for one week in August. From the figure, it is easily identified that the power output from the PV technology surpasses the energy required for the daily demand on a regular basis. The output reaches its peak during the day when solar radiation is at a maximum, and reduces through the evening as the sun sets. Due to the large daily spikes, the surplus energy can be stored by the batteries which is then discharged in the evening to be utilised. The output of the generator is relatively low when compared to the output of the PV panels on a weekly basis, as it produces a small amount of electricity to meet demand and keep the system stable. For the week in August, the generator only operates twice when there is insufficient PV power to meet the demand - August 20th and the night of August 22nd going into the early morning of August 23rd. The PV output reaches a peak of 6000 kW – 3 times the peak demand. Due to this daily surge of surplus energy production, the batteries have enough capacity to operate on a load following method – seen by the charge power of the batteries being in sync with the PV solar output - and the reason why the generator is sparingly operated.

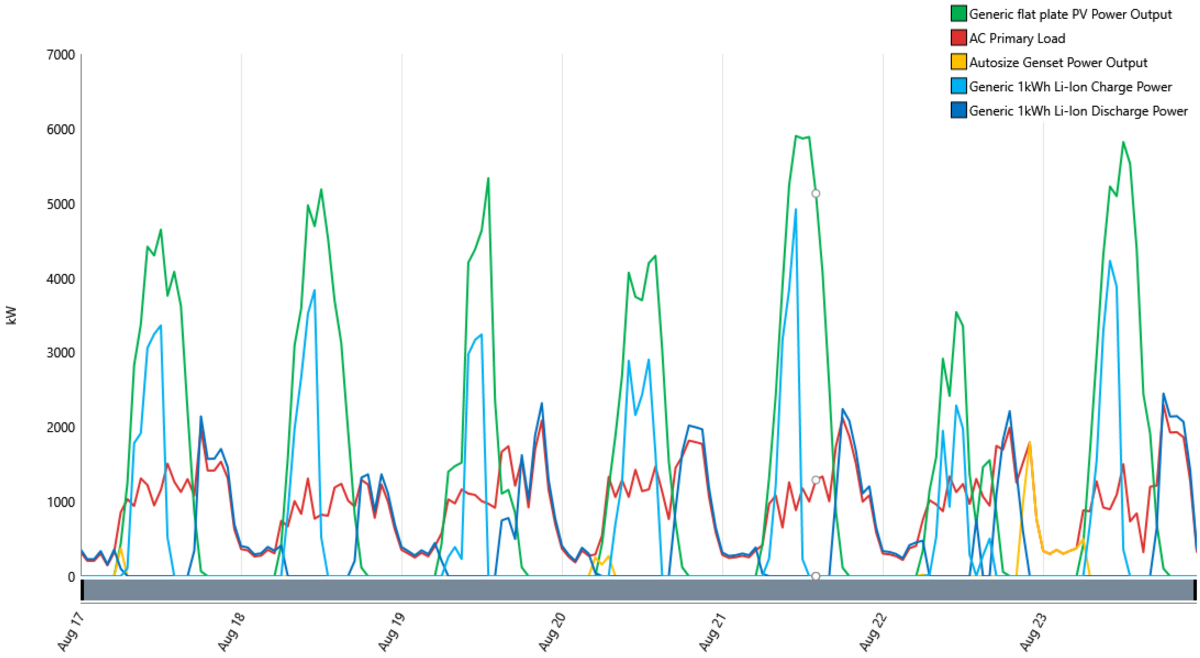


Figure 35- Supply and demand match for PV-diesel-storage hybrid system (August week)

The diesel generator is important to ensure stability due to the intermittent method of the solar resource. As during the colder months, there will be less solar radiation and in such instances the diesel generator will need to be switched on more frequently. An example is given in Figure 36 for a week in December when PV generation is low on numerous days. On these days, the generator is switched on to produce enough energy to meet the deficit between the supply and demand. The generator does not produce extra energy to be stored into the batteries which helps to reduce carbon emissions and increase the renewable fraction as the fraction is calculated through the amount of renewable energy used to meet the primary demand.

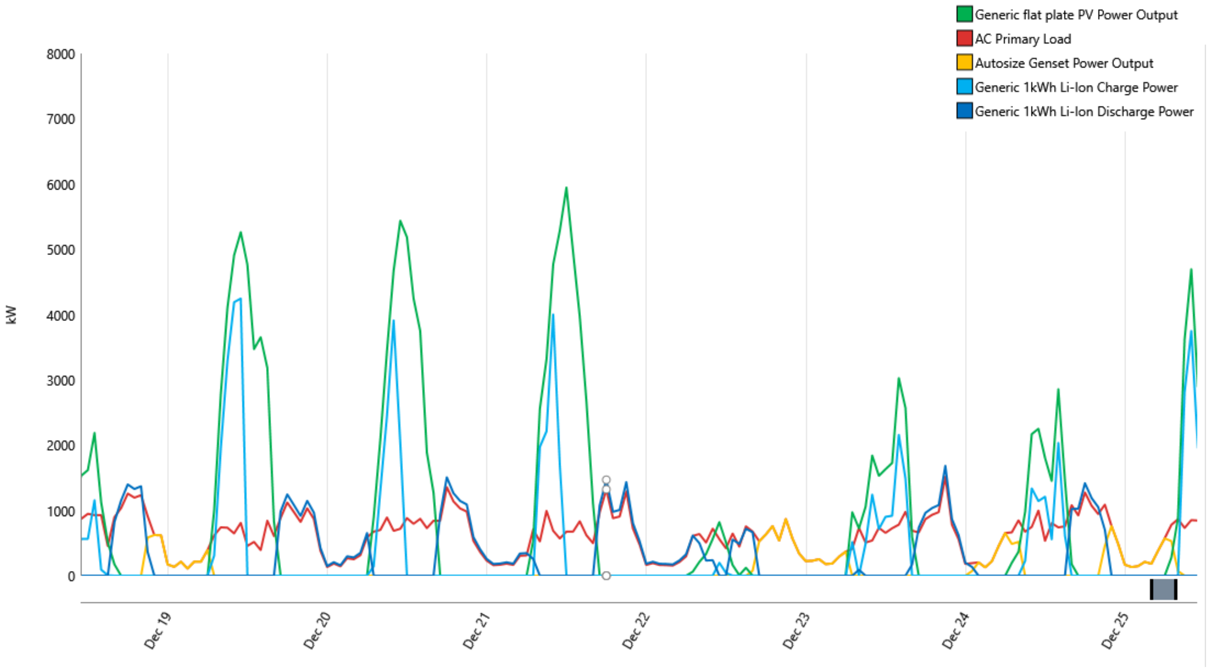


Figure 36- Supply and demand match for PV-diesel-storage hybrid system (December week)

From scenario 1 and 2, it is evident that the most suitable combination would be a diesel-PV system with energy storage to fully utilise the energy generated from solar resources. This type of system has the lowest carbon emissions, and has a high renewable fraction with a diesel generator which enables a secure electricity supply due to the intermittent nature of the renewable sources. It is also financially viable when considering future expected costs of renewables.

The next step of the modelling involved replacing the diesel generator with a biogas generator which utilises agricultural waste as a fuel source to recognise if this would provide a better system.

8.5 Scenario 3 Results

Table 15 - Scenario 3 Results

Unmet Load (kWh/year)	Ren Frac (%)	CO2 Emissions (kg/year)	COE ($)	NPC ($)	WT	PV (kW)	1 kWh Li	Generator (kW)	Converter (kW)
0.0	100	331	0.71	60,056,860	0	5,961	17,392	2,900	10,000
0.0	100	295	0.71	60,267,650	1	6,176	17,442	2,900	10,000
0.0	100	4,476	0.98	83,338,030	0	0	2,844	2,900	10,000
0.0	100	4,450	0.98	83,535,270	1	0	3,318	2,900	10,000
0.0	100	2,316	1.05	89,437,300	0	4,764	0	2,900	10,000
0.0	100	2,303	1.06	89,728,100	1	4,764	0	2,900	10,000

8.6 Scenario 3 Discussion

The simulations completed in Scenario 3 replaced the diesel generator for a biogas generator of the same size, using cots assumed for the present. A list of the utmost financially practical options is presented in Table 15.

All of the options listed in Table 15 have 100% renewable fractions, and zero unmet loads so the ideal system is selected on emissions and costs. Conversely, the combinations without storage are comparatively more expensive compared to the options with storage by $6 million. As mentioned before, systems without storage are included by HOMER based on net present cost, however, for the purpose of this investigation, systems without storage are not appropriate.

The inclusion of a biogas generator increases the net present cost – which is a representative of the overall lifetime cost of the system. This in turn, simultaneously increases the cost of energy. The benefit of including a biogas generator produces less carbon emissions when compared to diesel-renewable configurations.

The options which are cheaper simultaneously produce less emissions. This is due to the generators having reduced operating hours throughout the year. The two cheapest options do not vary much in carbon emissions or prices – depicted on Table 16. The difference between the two configurations of systems in Table 16 is that one configurations has a wind turbine, as before this system will not be suitable due to low wind resources.

Table 16 - Scenario 3 model systems

CO2 Emissions (kg/year)	COE ($)	NPC ($)	WT	PV (kW)	1 kWh Li
331	0.71	60,056,860	0	5,961	17,392
295	0.71	60,267,650	1	6,176	17,442

Considering this, the ideal and financially viable energy system would consist of a significant proportion of PV generation.

Ideal system for Scenario 3

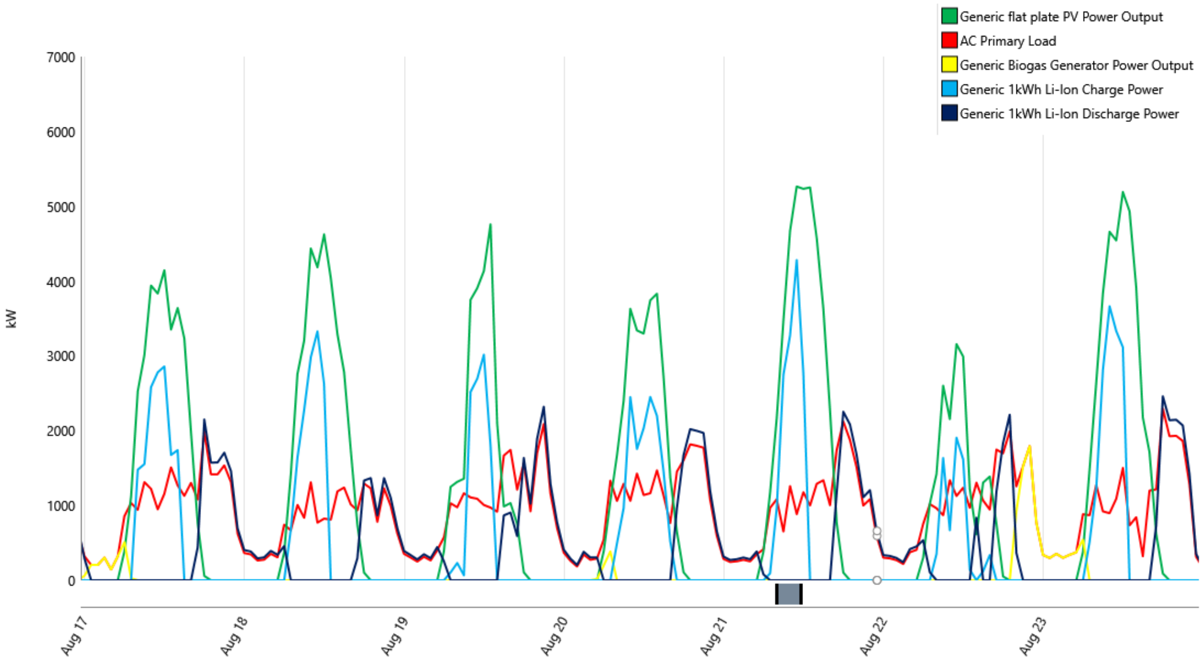


Figure 37 - Supply and Demand for Ideal system in Scenario 3

Figure 37 shows the supply and demand outputs for the ideal energy system which features a PV solar resources, 2900 kW biogas generator (operating for less than 1000 hours a year), a converter and 17,400 batteries as a form of energy storage. As before, the batteries charge when PV generation exceeds the energy required to meet demand. The surplus energy is then stored and used later in a load following operation to meet the demand as in scenario 2. The biogas generator only generates power when there is insufficient PV generation to meet demand. Both the batteries and biogas generator operate using the load following method as both only generate enough energy to meet the demand. From the ideal systems from scenarios 1, 2 and 3, it is evident that utilising solar resources is more viable in comparison to heavily utilising wind resources. This is due to the low average wind speeds as there is higher solar radiation it would result in a higher power output.

The final scenario had lower costs for solar and wind technologies similar to scenario 2, however utilised a biogas generator.

8.7 Scenario 4 Results

Table 17 - Scenario 4 Results

Unlet Load (kWh/year)	Ren Frac (%)	CO2 Emissions (kg/year)	COE ($)	NPC ($)	WT	PV (kW)	1 kWh Li	Generator (kW)	Converter (kW)
0.0	100	255	0.61	51,740,100	0	6,826	17,064	2,900	10,000
0.0	100	235	0.61	51,933,060	1	6,743	18,058	2,900	10,000
0.0	100	2,213	0.98	82,807,380	0	6,257	0	2,900	10,000
0.0	100	2,231	0.98	82,994,540	1	5,830	0	2,900	10,000
0.0	100	4,476	0.98	83,338,030	0	0	2,844	2,900	10,000
0.0	100	4,459	0.98	83,473,900	1	0	3,318	2,900	10,000

8.8 Scenario 4 Discussion

The final scenario had simulations run which were similar to scenario 3, however the prices of solar and wind technologies were estimated for future cost values.

The results for this scenario (Table 17) are not largely different. It can be seen that there is a larger PV capacity compared to scenario 3, this would be due to the costs lessening for solar technology. In turn, this reflects an overall lower cost for the systems that feature solar heavily, in turn reducing the cost of energy significantly. Although wind technology has also decreased in price, there has not been a drastic increase in the quantity of wind turbines, due to the weak wind resources that do not make it financially feasible to have turbines.

The ideal system was selected based on financial merits and emissions produced as all configurations had 100% renewable fractions and zero unmet load. The cheapest options produced the lower amount of emissions. The higher priced systems were considered inadequate due to their high volume of emissions in addition to the costs. The two options remaining – which contained storage – differed again due to a turbine, and so the ideal system was considered to have a large PV capacity with a large storage capacity as well.

Ideal system for Scenario 4

The ideal system for scenario 4 is similar to the ideal system for scenario 3 – shown in Table 18 – the system has a higher PV capacity due to the lower cost of the PV technology. In turn, this has resulted in reduction of carbon emissions, as there is an increased surplus of PV generation which can be stored in times of excess production for reuse later – also becoming an autonomous system due to the zero unmet load- and a reduced cost by $8 million with a $0.10 reduction in the cost of energy when compared to the ideal system of scenario 3

Table 18- Ideal System from Scenario 4

Unmet Load (kWh/yr)	Renewable Frac (%)	CO2 (kg/yr)	Cost/NPC ($)	COE ($)	WT (no)	PV (kW)	1 kWh Li
0	100	432	51,740,100	0.61	0	6,826	17,064

Figure 38 shows the demand and supply of the ideal system for scenario 4. It is similar to the ideal systems for scenario 2 and 3, as it has a high PV generations where surplus energy is stored in the battery as the charge line mimics the PV power out line. The biogas generator is switched on only during times where PV generation is not sufficient to meet demand – on August 20th and August 22nd. The generator and batteries operate in a load following mode, so the generator is not producing any surplus energy, which results in lower emissions as the generator is running for less hours throughout the year.

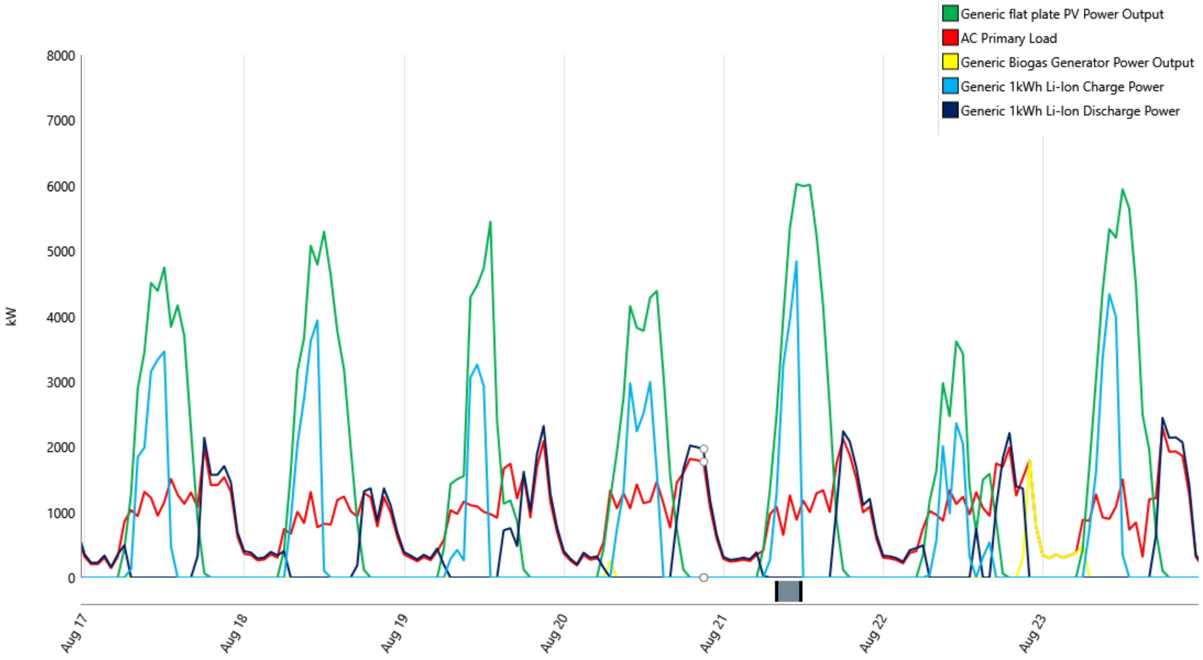


Figure 38 - Demand and supply for ideal system for Scenario 4

From the simulations in the scenarios that have been computed, it is evident that the ideal system would have a large PV capacity. The addition of energy storage is needed to store excess electricity which can be reused in times of higher demand, as times of peak supply will not match peak demand. Including storage capacity would also stabilise a system which generates large proportion of renewable energy. The generator operates for 720 hours per year, which is feasible with the land available associated to the case study.

The most suitable system for a rural application in the case study, from the scenarios, primarily constitute of PV generation and storage, with a generator being used to meet demand when solar radiation is inadequate to produce sufficient energy. Although HOMER provides an insight to the best available options through its Optimiser feature, HOMER bases the optimum solution solely based on net present costs. A real life system would need to consider more than one factor, and so HOMER cannot provide the answer for the ideal system but can aid in identifying the best technological combinations which can be utilised.

9. Sensitivity Analysis Results

A sensitivity analysis was completed to see how changes in certain variables would affect the configuration of the energy system.

Effect of energy storage

It is important to note the effect energy storage can have on the variables analysed to identify a suitable energy system. A comparison is presented in Table 19. The table shows that the addition of storage capacity dramatically decreases the cost and required PV capacity. This is significantly a result of the storage capturing any excess electrical production during times of peak supply, charging it to a battery and then utilising this energy in times of increased demand (where supply may be low or non-existent from PV technology). This in turn reduces the reliance on diesel, in turn lowering the carbon emissions of the system. As more energy generated from PV panels is utilised, there is an increased renewable fraction, regardless of the PV capacity being lower than the system without energy storage.

Table 19 - PV system with and without energy storage

1 kWh Li	PV (kW)	Generator (kW)	CO2 (kg/yr)	Renewable Frac (%)	Cost/NPC ($)
0	2,526	2,900	5,078,970	2.7	$42,711,140
2,808	1,950	2,900	3,460,296	27.1	$30,642,620

Effect of increased fuel price

The effect of increasing diesel price is evident from Table 20. As the price increases, the capacity of renewables increases. This is because the renewable systems become more financially viable especially when the diesel price reaches $2/L. With increasing diesel price comes an overall increase in costs as the hours of generator being used is reduced as a result of fuel becoming more expensive. This would be similar for biomass, although Table 20 only shows diesel fuel prices.

Table 20 - Systems with increasing diesel price

Diesel Price ($/L)	Wind Scaled Average (m/s)	PV (kW)	WT (no)	Generator (kW)	1 kWh Li	Cost/NPC ($)
0.50	8.00	701	16	2,900	2,598	$25,200,000
1.00	8.00	877	19	2,900	2,591	$29,300,000
2.00	8.00	2,535	21	0	9,821	$30,000,000

Effect of increased wind scaled average

As the wind scaled average increases, the capacity of the PV decreases generally. While the capacity of the number of wind turbines increases, this is because as the wind speed increases it becomes progressively financially valuable to have a larger number of wind turbines as it will result in higher power output when compared to PV power output. There is an overall effect on the costs, but only if the wind scaled average is increased dramatically as seen in Table 21.

Table 21 - Increased wind scaled average on system

Diesel Price ($/L)	Wind Scaled Average (m/s)	PV (kW)	WT (no)	Generator (kW)	1 kWh Li	Cost/NPC ($)
0.5	3	1,877	0	2,900	2,852	$30,600,000
0.5	3.44	1,950	0	2,900	2,808	$30,600,000
0.5	8	701	16	2,900	2,598	$25,200,000

There are many factors that affect the type of system which can be identified as “ideal.” The addition of energy storage is vital for a system to have a lower cost, missions and a higher renewable fraction. An ideal system should contain energy storage. Both average wind speed and fuel price also affect the configuration of the ideal system, and so this should be taken into consideration when identifying the model energy system for rural application, as these variables – as well as others – may influence the configuration dramatically.

10. Conclusion

The use of storage is essential in a system which features significant renewable generation as it increases the stability of a system, while also increasing the renewable fraction as a larger fraction of the load is met using renewable energy when the surplus is stored. Wind turbines are not financially feasible due to the low wind speeds of the case study, however in areas where there are increased wind speeds they could be better utilised. The price of diesel is susceptible to drastic increases due to the limited reserves of fossil fuels – which are depleting. As seen from the sensitivity analysis, the increase in diesel fuel results in the increase of the renewable capacity of a system as it becomes more financially feasible. With the current costs of renewables, it is difficult to design an energy system which features large renewable generation that is financially feasible. Nevertheless, as the future prices for renewables are expected to drop, this would encourage more renewable capacity in a system. In turn, this would reduce carbon emissions, as an increased renewable capacity would result in the generators operating for less hours.

Although HOMER provided an initial insight into what configurations are financially viable, it does not consider all of the important factors required for a rural energy system. This is a limit of the program, as it considers systems which contain high renewable fractions and no storage financially feasible but does not consider the practical feasibility of a system. This is one of the limitations of the software package.

It can be concluded for the case study of Chak 111/12L, Chak 112/12L and Chak 113/12L, an ideal system would incorporate PV technology and batteries (as a form of energy storage) heavily, with a generator to provide a secure electricity supply. This was evident from analysis of the financially feasible systems provided by HOMER. As solar resources are intermittent and unreliable, it is important to include a generator of some form which can produce electricity during times when solar resources are low. The desired generator should be a biogas generator as it produces less emissions compared to a diesel generator which justifies the increase in costs. The diesel generator would also be susceptible to fuel shortages in the future due to reduced fossil fuel reserves, and so would be unsustainable, while the biogas generator could utilise agricultural waste as a fuel source. It should be noted that although a system with significant renewable generation is achievable through software, it would be difficult to implement it in a real life scenario as renewable resources will differ on a year by year basis.

10.1 Future Work

The results of the investigation concluded that the ideal energy system for rural communities in Punjab, Pakistan, would consist largely of PV capacity, storage capacity and ideally a biogas generator to produce the deficit between supply in demand when solar resources are low.

The optimal system may change if other storage technologies could be utilised. If future work was to be completed on the research mentioned within this thesis, it could consist of designing an optimal system considering a mix of different storage technologies and generation technologies, such as flywheel, pumped hydro or hydrokinetic. It could also include a larger sample spread evenly throughout the case study villages in order to produce a more accurate demand profile which in turn would aid in the construction of an optimal energy system for rural communities.

11. Appendices

11.1 Appendix 1 – Calculations for viable operating hours of Biogas Generator

From Saeed's research, a year's collect6ion of agricultural waste totalled 135,716.4 MT.

This converted to kg equals: 135,716.4 x 10^6 kg/year

$$\frac{mass\ of\ agricultural\ waste}{agriculture\ land\ in\ Pakistan} = \frac{135{,}716.4 \text{ x } 10^6 \text{ kg}}{374{,}164.65\text{km2}}$$

$$= 362{,}718\ kg/km^2/year$$

$$= 362.7\ tonnes/km^2/year$$

$$= 0.994\ tonnes/km^2/day$$

$$= 1\ tonne/km^2/day$$

When using the fuel curve, it showed that there were 6 tonnes/hour required to produce similar output as the diesel generator. This equates to 144 tonnes/day.

If the area of the land for the three villages has been calculated to have an area of 17.26 km^2, then this will produce:

$$17.26\ km^2 x\ 1\ tonne/\ km^2/day$$

$$= 17.26\ tonnes/day$$

Assuming 100% of the area calculated is used for agricultural, there is even waste distribution for all types of agricultural produce, and that all days in the year produce some form of agricultural waste →17.26 $tonnes/day$ x 356 days/year

= 6,300 tonnes/year

Considering 6 tonnes/hour are required:

$$\frac{6{,}300\ tonnes/year}{6\ tonnes/hour} = 1050\ hours\ of\ biogas\ generator\ operation\ per\ year$$

This would be the maximum viable hours of operation per year. If the hours of operation for the biogas generator are higher more agricultural waste or biomass would need to be sourced.

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