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DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

Power grid architectures for Sub-Saharan Africa

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Abstract

This project is designed to address the chronic lack of energy access in Sub-Saharan Africa, particularly for rural communities. This will be achieved by selection and optimization of key power supply elements aided by simulation. The selected components will be connected and simulated in the program HOMER Pro 3.7 which offers power grid optimization and financial analysis. The project more broadly is based on problem oriented research of both quantitative and qualitative nature. The subject area is broad and the project is intended to be an introduction to the specific issues around microgrid design. Principles of both electrical and electronic engineering are introduced and used throughout. Subjects of business and management are used for costing and economic analysis. Much of the project is based on judgement by methods of inductive and abductive reasoning.

A literature review and study of the key components that make up low cost energy distribution systems is presented first. Solar and hydropower are chosen as the most suitable generation forms and a microgrid topology is chosen to support them. For storage; lithium-ion batteries, lead-acid batteries, and pumped hydro energy storage (PHES) are selected and simulated for performance comparison. Various control methods are examined and compared for suitability and it is found that voltage based control methods can be used without communication architecture. Reversed droop control with maximum power point tracking (MPPT) and prime mover speed control are the control methods deployed. The inputs for simulation are taken from real life example renewable microgrids (Rushunga & Rubagabaga) in Rwanda. The results from these simulations show microgrid viability for medium and low level consumers with both solar and hydro sources. The associated costs are compared to that of the national grid and it is shown to be similar. It is also found that li-ion batteries are the superior storage option for these environments. PHES most likely cannot be used for microgrid storage as it is underutilised due to size and the costs associated are high.

1 Introduction

This is an engineering research project on power grid topology design for the unique geographical and social conditions that exist in Sub-Saharan Africa. Sub-Saharan Africa has been chosen as it is an area of the world with incomparably low levels of electricity access for citizens. Much of the research in power and electrical engineering today is focussed on improving large scale centralized grid structures. While existing grid networks are in need of innovation and improvement, much of this insight is not applicable to communities that as of yet have little or no electricity access. The aim of this project is to apply some of these insights to produce a grid structure that is cost effective, deployable on a large scale, and future proof. The structure should rely entirely on renewable energy sources and provide a supply of power that is reliable and safe. The structure will be designed for rural communities in Rwanda but should be appropriate for any country in Sub-Saharan Africa.

First the motivation and specific aims of the project will be presented. The following section introduces Sub-Saharan Africa and Rwanda in particular in terms of climate, economics, and existing power infrastructure. Next existing power system technologies will be presented and discussed; these include architectures, renewable energy sources, storage technologies, and control techniques. Then these technologies shall be applied to the formation of two grid systems that will both be simulated and optimized. The results of these simulations will be discussed and further improvements explored.

1.1 Motivation

The motivation for this project can be explained largely by figure 1.1; Sub-Saharan Africa has a remarkably low rate of electrification, even when compared to other developing nations. The problem is even more pronounced for rural communities where extending the national grid is expensive and, for particular areas, may even be impossible.

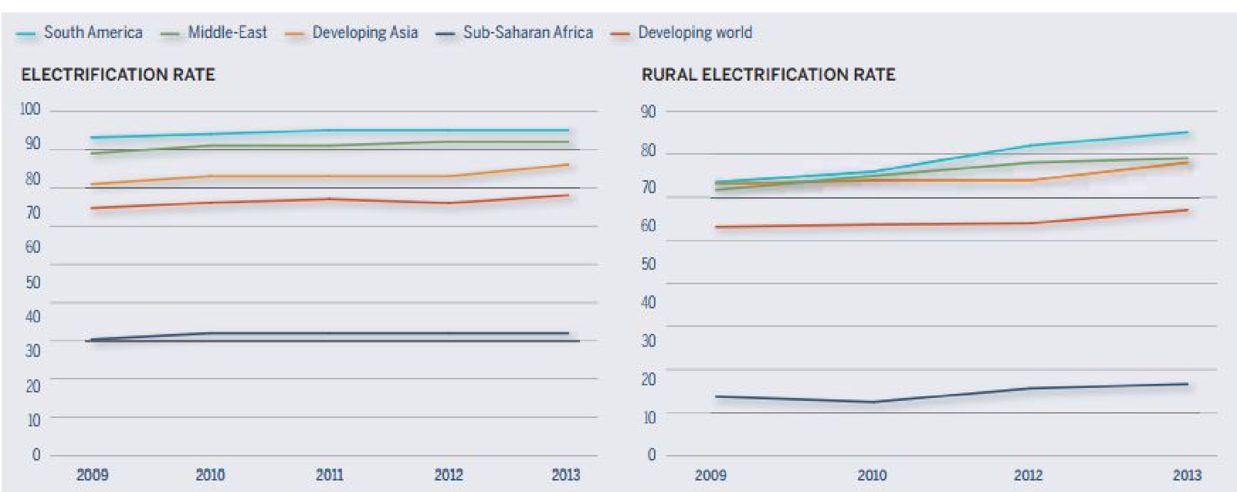


Figure 1.1: Rate of Electrification in the Developing World[1]

The reasons for this are not fully understood and part of this paper will be to attempt to explain the unique characteristics of Sub-Saharan Africa that lead to this striking lack of electricity access. Partly it may be explained by the lack of economic growth, infrastructure, and resources that electricity rollout schemes typically require. While these factors do not fully explain the situation it is clear there is a need for a low cost electrification strategy that can encompass the whole region. Much of this strategy is past the scope of this project including much needed political, legal, and economic progress.

This project will focus on the engineering solutions required for the region particularly on the needs of rural communities. Some of the areas in which engineering can reduce cost burden for investors are energy efficiency, demand management, optimal generation planning, and improved grid operation[2]. The focus here will primarily be on optimal generation planning and demand management while analysing the cost benefit of distributed microgrids for rural communities.

There is much evidence to suggest that the supply of electricity is the key step required to break the cycle of poverty. Electricity is now seen as one of the most basic building blocks to building a more prosperous community. As explained in the Poor people's energy outlook 2014[3]: '*Energy is fundamental to poverty reduction and a critical enabler of development'* and that '*more decentralized, off-grid energy provision will be required than conventional, grid-based energy. This has been evidenced since 2011 but largely ignored by policymakers and the energy community thus far*'.

The impacts of electricity can be categorized into income related and non-income related benefits. Income related benefits include lighting that increases productivity and studying time for children, water pumps for irrigation, mechanical power for industry, and mobile phone use. Non-income related benefits include reduction of smoke inhalation diseases from open fire cooking, food and medicine refrigeration, and reduction of the use of biomass which must be collected or bought. These are just a handful of the benefits of energy access for those in poverty, there are countless more which are well documented and researched, examples are [3], [4] & [5].

1.2 Aims and Objectives

The overall aim of this project is to design a functional safe power grid design for rural communities across Sub-Saharan Africa. The general and specific functional objectives for the system and project are as follows.

I. Serve village sized community with variable energy requirements
   i. Supply at least 600 people
   ii. Supply enough power for conventional white goods (Refrigerator, freezer, etc.) defined as 2kWh/day/household
   iii. Supply both residential and commercial loads with realistic load profiles
II. Achieve a low cost that is in line with regional income.
   i. Net present cost (NPC) of less than $200,000 for whole system
   ii. Levelised cost of energy (LCOE) of less than $0.3/kWh
III. Achieve a stable supply with high efficiency and power quality

i. Load connection at 230V 50Hz AC
ii. Load factor of over 40%
iii. Unmet load of less than 10%

IV. Analysis and selection of optimal storage solution
i. Literature review of low cost energy storage solutions
ii. Optimization of storage technology in HOMER to determine size

V. Analysis and selection of optimal control and dispatch methods
i. Literature review of control methods
ii. Analyse qualities of grid for control selection
iii. Selection of low cost control method directly deployable within existing system structure

VI. Minimal carbon dioxide emissions
i. Purely renewable energy sources
ii. Locally sourced materials where available

2 Characteristics of Sub-Saharan Africa

Sub-Saharan Africa is defined by the UN as consisting of all African countries that lie fully or partially south of the Saharan desert[6]. The nations of South Africa and Mauritius will be excluded from the definition for this paper due to their relatively high electrification rate and economic indicators compared to the majority. Nigeria has a high grid connection rate but the overall generation and reliability are too low to sustain reasonable useage so Nigeria will be included regardless.

Rwanda is a small landlocked country in Central Eastern Africa, bordered by The Democratic Republic of Congo (DRC), Uganda, Tanzania and Burundi. It has a young population of around 11 million, relatively low corruption levels and an elected government that has made broad strides to reduce crime and increase private investment over the last decade. Rwanda has been chosen specifically because of its recent economic and regulatory success which, it is hoped, could be emulated across the continent.

2.1 Climate

Most Sub-Saharan nations are either hot desert or tropical climates although there is a large variety over the total area. The region is characterised by high solar irradiation throughout with sporadic river systems concentrated mostly in the tropical countries.

Rwanda has a temperate tropical highland climate with two rainy and two dry seasons a year. It lies in the drain basins for both the Nile and the Congo rivers[7]. These features give Rwanda a large number of river systems that are naturally compatible with hydroelectric energy. Rwanda is highly mountainous and often called the ‘land of a thousand hills’[8], the landscape forges a large number of rivers. During the dry seasons however the river systems partially dry up. Between

June and September each year there can often be no rain at all which drastically reduces total river flow rate.

Open Energy Information (openei.org) gives the following energy resource data for Rwanda, from the National Renewable Energy Laboratory (NREL) and the CIA world factbook.

Resource	**Value**	**Source**
Wind potential	~0 m/s (at 50m)	NREL
Solar potential	66,786,631 MWh/year	NREL
Natural gas reserves	56,630,000,000 m^3	CIA
Oil reserves	0 Barrels	CIA

These figures give a clear picture of the unique climatic features of Rwanda, particularly that there is virtually no wind potential and no oil. These figures are not unusual for the region, while some of the surrounding nations have oil reserves there is very little wind potential in Central and Eastern Africa.

2.2 Economy

The various populations within Sub-Saharan africa show huge diversity, there are countless languages, sub-cultures, tribes and religions that populate the area. Average figures for human development index[9], life expectancy, and literacy levels[10] are some of the lowest in the world. Sub-Saharan Africa as a whole is characterised by stagnant economic growth, high rates of poverty. Regional drought, famine, and instability plague economic markets, inhibiting any real sustainable growth. Population density is relatively low[11] with a large rural farming population.

Rwanda is a small nation within the continent and it has a much higher population density than others around it which should make power grid extensions easier and less expensive. Rwanda currently has an agriculture based economy with fertile land perfect for growing Tea and Coffee. These are the two largest exports and 90% of the population are involved in the industry[12]. The national currency is the Rwandan Franc (RFw), $1 USD is equivalent to 825RFw (or RWF) at the time of writing.

The 1994 genocide in Rwanda largely destroyed the local economy and in the years after there was very low investment and growth. However, after a few years it stabilized partly due to a relatively strong government. The Rwandan economy has now made a full recovery and is one of the fastest growing in the world with a yearly GDP growth rate between 2001-2014 of 8%[13] while inflation remains relatively low. This is part of the reason why Rwanda is a good candidate for this study as it exemplifies a model of how other African nations may be able to break free of poverty and establish investor centric economies.

The energy market in Rwanda is small which, combined with other factors such as regulation, geography, and recent history make energy costs much higher than other countries in the region. The charge to a consumer for connection to the national grid in Rwanda is $350 while in Sudan, for example, it is $38[14]. The high investment costs are present in almost all markets, [15] shows that a typical hydro project in Rwanda will cost double the average. The high costs pervade all aspects of development from the distribution network, the civil works, and loan conditions given to investors. The microgrid market in Africa is growing but energy access on the continent is still seen by many as an issue of charity rather than an opportunity of business. The companies that are currently operating the kind of business model this project is based on, such as Powerhive (powerhive.com), are small so the market remains low scale. The government is aware of this issue and has taken bold steps in recent years to increase bulk investment and electrification rates have increased accordingly but more must be done.

2.3 Infrastructure

The entire generating capacity of Sub-Saharan Africa is around 68GW[2], roughly the same as Spain. There is huge variation in development across the region as 70% of this generation lies in South Africa so the actual rate for the other countries is even lower than expected.

Electrification rate can be measured in a number of ways depending on definition, for example some measurements require a constant supply whereas others require just an hour daily access for a consumer to be considered connected. The World Bank measures current national rate for Rwanda as 27%, the rate for rural populations is around 10% although other rural measurements are as low as 1%[16][1]. The government has made promising progress (figure 2.1) in the last decade especially for urban communities where the cost of grid extension is low.

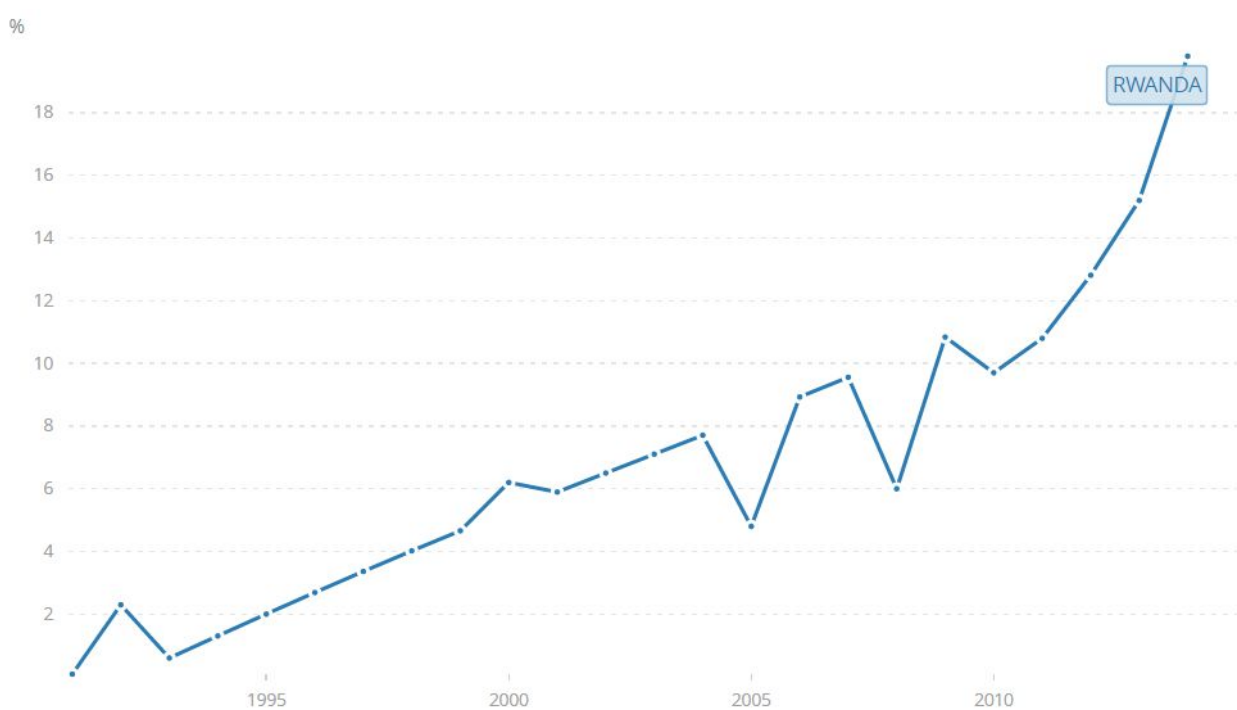
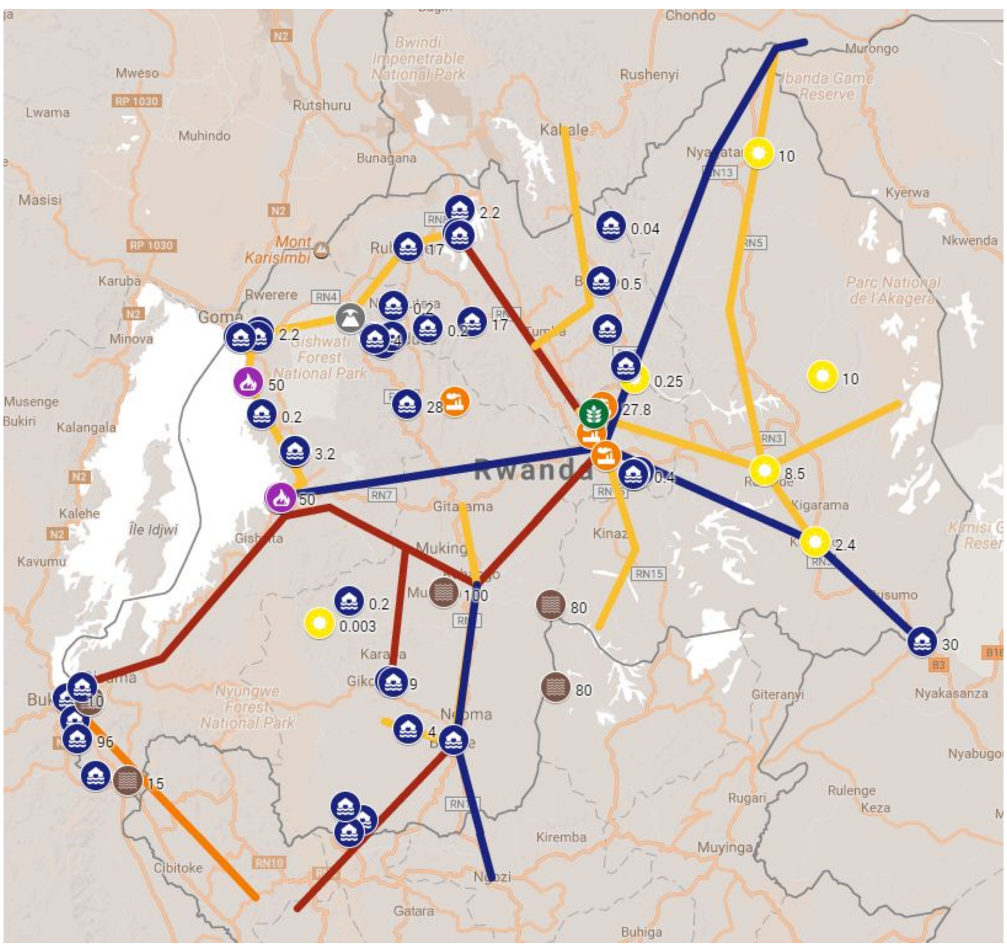


Figure 2.1: Rwanda rate of electrification over time[13]

Despite the progress these figures put Rwanda below even the Sub-Saharan average. The power grid that does exist in Rwanda is structurally weak and covers only a fraction of the country. The grid has estimated losses of 23% nationwide[17], this figure should be considered carefully as it includes non-technical losses but it is still far higher than the UK with losses of 1.77%[43]. Additionally the country has a huge oil trade deficit, as there are no proven petroleum resources within Rwanda all the oil used in the country must be imported. Over the period 2000-2012 oil consumption within Rwanda rose 16%, the cost of the oil rose over 700%[17]. All of this has resulted in a Rwandans paying a huge price for their electricity. As [19] states; there has been a '*rapid growing of the cost of energy per kWh, 17 RWF in 1995, 42 RWF in 1997, 82 RWF in 2005, 112 RWF in 2006 (VAT not included)'.* This is a pressing problem for a country that is aiming for long term energy independence and the investment needed to increase energy access, secure grid stability, and reduce foreign oil dependence is huge. Despite these figures, the government remains optimistic with electrification targets of 70% by 2017/18 and 100% by 2020[18].

A full map of the transmission and generation network in Rwanda, developed as research for this project is shown in figure 2.2. Both current and future nodes are included to easily visualise current development strategy. An interactive version including additional information can be found at goo.gl/z15duQ.



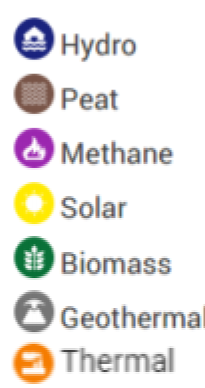


Figure 2.2: Power Infrastructure in Rwanda (Including planned resources)

The data used to make this map is mostly sourced from the Rwanda Energy Group (REG), as well as various articles and online sources. The generating output of selected nodes is shown next to their location in Megawatts. The blue lines are 220kV transmission lines, red are 110kV, orange are 70kV, and yellow 30kV.

The significance of both large scale and micro scale hydro power in Rwanda is evident from the data collected. The total Hydropower in Rwanda is estimated at 400MW with 98.5MW currently utilised. Many villages and communities are powered by micro hydro grids, particularly in the mountainous north-west where there are thousands of rivers and streams to draw from. The Rwandan Hydropower Atlas found that the majority of new feasible sites were between 50kW and 1MW in capacity[17] making Microhydro the dominant resource across the country.

Large hydropower projects are also underway, the recent regional peace and stability has allowed for highly productive international co-operative energy projects such as the Ruzizi Hydropower dams. The Rusizi river lies along the South-Western border and powers two stations already. Plans are to continue building to at least 4 stations, the most recent has an output of 96MW. These resources are shared equally between Rwanda, Burundi and DRC, countries that were at war just 10 years ago. However, hydropower is not perfectly reliable and Rwanda's seasonal pattern can mean shortages in the dry months. Climate change due to global warming is exacerbating the problem. As recently as 2004 Rwanda experienced an extended dry season over 2 years that reduced the combined generation from two of the largest hydropower stations from 23.7MW to just 7.5MW[19]. Solar power is being deployed across less wet regions, much in the form of solar home systems (SHS) and a few larger installations. Solar is often the second choice due to the higher capital and maintenance costs that are largely avoided with hydro.

Resources [17] and [18] are the Rwanda Ministry of Infrastructure's *Energy Sector Strategic Plan* and *Rural Electrification Strategy* respectively. These documents give insight into the priorities of the government and the ideas that they are considering publicly. The papers suggest that Rwanda is aiming for a strong, centralised national grid based on large scale hydropower but concedes that off grid solutions can be the most cost effective option for low income and low demand customers, stating:

'*Advances in technologies, along with reductions in cost, mean that off-grid solutions can be the most cost-effective way of providing essential energy services for a significant proportion of households. Because off-grid systems can be scaled to meet demand requirements, they can provide an affordable and flexible way for households to start progressing up the energy ladder, particularly for those on low incomes.*'[18].

The *Rural Electrification Strategy* states that new mini-grids must conform to standards agreed with Rwanda Energy Group (EUCL) in order to future proof them for connection. Additionally they state that the operators of mini-grids will be required to commit to standards of service such as maximum outage time although these standards remain undefined.

Other energy sources, either in operation or under analysis in Rwanda include biomass in the form of the Kibuye sugar works, peat-to-power in the south, methane gas extraction from the western lake Kibuye and geothermal energy resulting from the volcanoes in the East African Rift. While each of these sources may be beneficial to Rwanda in the future it is uncertain which, if any, are replicable in the rest of Sub-Saharan Africa. Additionally, geothermal is the only of these energy types that is generally considered a true renewable. Therefore these sources will not be considered as appropriate energy sources for this project.

3 Power system architectures

The unique conditions of Sub-Saharan Africa require a unique power supply solution. The following section will present a number of power supply technologies and comment on their suitability for the region. The technologies chosen are to be highly inter operable so that a concise whole may be presented at the end. The final grid designs will be simulated in a computer program called HOMER. HOMER is a leading grid simulation program designed by the US National Renewable Energy Laboratory (NREL). It takes general grid parameters as inputs and outputs an optimal least cost system based on the constraints defined. For figures that are not definitive there is an option to define 'sensitivity variables', HOMER will simulate the operation for all of the sensitivity options and give the optimal system for each scenario. This allows the user to see the effect of each variable and it will be used here for values that are subject to change or for comparison. Some of the concepts in this section are based on the Power Theory Fundamentals section in Appendix I. The functionality of HOMER is fully described in Appendix II along with the values given for project parameters not included here.

3.1 Grid structure

Power can be delivered to consumers in a number of ways, generally categorized by size from national and international power grids to solar panels powering a single home. Grid structure is used here to mean all aspects of the design of the grid including size, components and voltage level. Often these aspects of a grid are dependent on each other under the laws of electricity.

Currently most large scale national grids encompass AC 'passive radial distribution'. Passive describes the nature of the grid, transformers increase and decrease voltage but there is no active management of power flow. Radial describes the structure of the network as a set of generators feeding out power radially to substations. The voltage level at large sources like coal and nuclear power plants is around 20kV. Transformers increase the voltage to up to 400kV for long distance transmission. The voltage is reduced in steps at substations around the country decreasing in voltage at each substation until it reaches the consumer who will experience around 230V. Passive radial distribution has worked for decades and is still the assumed topology for almost every electrical grid in the world. In more recent years there has been an ever increasing proportion of the grid-connected population that is generating their own power. Distributed generation (DG) is any generation of power away from a power station, it could be a community hydro power station or a garden wind turbine. Passive radial grid structures are not suited to this type of addition as DG units are effectively trying to send power the wrong way up a one way street. As the proportion of DG on the grid increases further there is a pressing need for fundamental changes in power systems.

One option is to update the existing grid to accommodate the new DG, and this is the only feasible option for countries with existing well-formed grids. The grid could also stand to benefit from an overhaul in other ways, such as deployment of accurate sensors, increased control, added functionality for electric vehicles, replacement of old hardware, and updating of the system to incorporate modern electronics and computer software. The transformation that must take place has been compared to that of the telecom industry[20] from public switched telephone network to broadband, wireless and fibre. The infrastructure of the modern grid must be completely rethought and updated. These plans are all part of the formation of the ‘smart grid’, a concept very much at the forefront of recent electrical engineering research. Much like the telecoms transformation, Africa has the opportunity to leapfrog traditional structures and incorporate the refined technologies straight away. Public switched telephone networks were never established across much of Sub-Saharan Africa but once the cheaper cellular technology became available Africa deployed it rapidly.

As explained in [21], one problem for Africa in developing large smart grids is that it is prohibitively expensive as the inhabitants are spread over such a vast area. In 2015 the Association for the Development of Energy in Africa (ADEA) assessed a plan for universal electrification across Africa by 2040 and the total cost came to $884 billion. As well as high cost the distances in Africa for electricity transmission are so large that power losses become more significant. For every added kilometre of transmission distance the cost and the power loss increases. A different strategy must be deployed to rapidly increase access to electricity across Africa in a way that does not penalise rural communities.

An alternative that is suited to rural communities is to combine DG with Distributed Storage (DS). DS is local energy storage and, when combined with DG, can form the basis of a microgrid. Defined by the DOE Microgrid Exchange Group[24]:
“*A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.*”

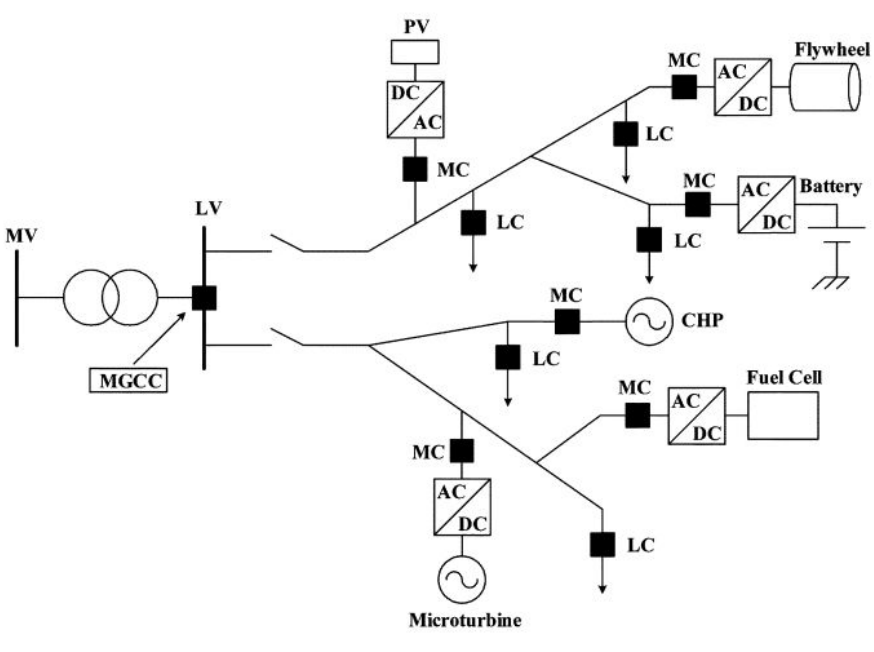


Figure 3.1: Microgrid Architecture[25]

Figure 3.1 illustrates an example low voltage (LV) microgrid connected to a medium voltage (MV) wider grid by point of common coupling (PCC) switches. The microgrid hosts sources (PV, CHP), storage (Battery, Flywheel), microsource controllers (MC), and load controllers (LC). The central control is provided by the microgrid central controller (MGCC).

Distributed power systems bring many benefits as opposed to centralised systems, in [22] the authors show that decentralised development projects are much better suited to dealing with construction and budget disruption. [23] shows that, while for most countries a centralised system is cheaper, in Africa decentralised development can be more cost-effective.

While some papers suggest refer to islanded microgrids as 'emergency mode' and grid connected as 'normal mode'[26] there is no essential reason that a microgrid must be grid connected. Islanded microgrids can be functionally stable and designed so that future connection to a larger grid is cheap and simple. The internal 'fixed' costs of building the architecture of a microgrid can be substantial. This naturally motivates the government and utility companies to expand the grid to that node in the future as it would only require a single PCC connection rather than individually connecting each building. Additionally; connecting to a microgrid brings electrical benefits as it can supply excess power and add stabilization. These two motivators give governments and companies an economic incentive to connect to microgrid communities, furthering their prosperity, income, and stability. For many rural communities in particularly isolated areas an islanded system is the only option and the grid may never reach them. For these people a microgrid or nanogrid is the only option of electricity access.

To give perspective to the possible power requirements of a microgrid in Rwanda it is useful to refer to some real life examples. These projects show the operational and economic feasibility of pure renewable microgrids in Rwanda. One operational solar microgrid is that of Rushonga, eastern Rwanda. The grid supplies 40 local businesses and 140 families with a 35kWp solar power base station. It is a private venture by Neseltec LTD, facilitated by the The Energy and Environment Partnership (EEP)[27]. The microgrid designed here will serve 150 residential households and 20 local commercial buildings entirely on solar power, each load experiencing a grid-like service. A population of 600 is served which assumes an average of 4 people per household.

One of the many hydropower microgrids in Rwanda is the Rubagabaga village grid on the Rubagabaga river in the northern province. There is a 50kW turbine that supplies a minigrid of a school, a village centre, various industrial businesses and 314 households consisting of approximately 1,238 people[28]. A separate 350kW turbine is connected to the national grid, as displayed in figure 3.2.

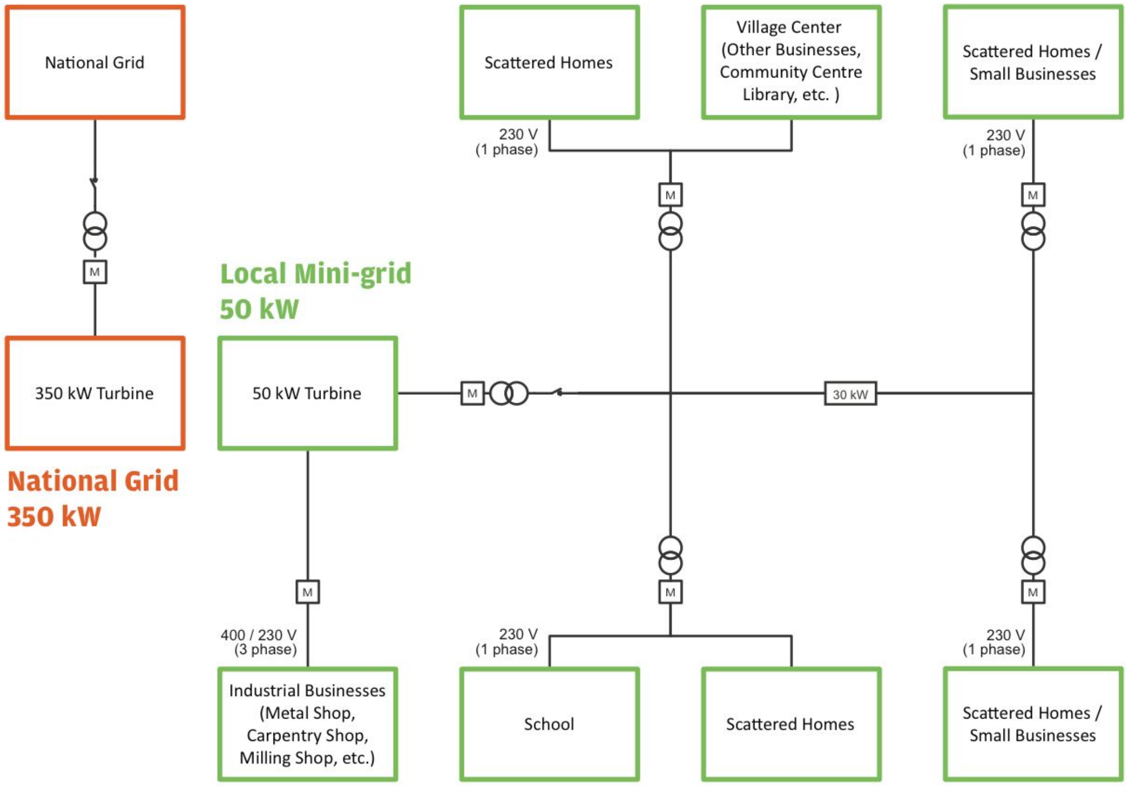


Figure 3.2: Rubagabaga minigrid layout[28]

3.2 Load

Load is the term for a point in a grid at which power is consumed. The load in this case describes any consumer that draws power from the grid. There will be both residential and commercial load types for the village. Residential load consumption patterns, also known as load profiles, are generally characterized by medium peaks in the morning and large peaks in the evening with low consumption through the day. In many African countries it is common for farmers to come home for lunch which increases the residential load at midday. Commercial loads are similar but the load profile is more flat with consumption consistency throughout the day.

HOMER can generate generic load profiles for both residential and commercial loads, if provided with an average daily energy consumption in kWh the profile is scaled to that level while retaining the original shape. To find the daily consumption for the village some assumptions must be made. The current average electricity consumption in Rwanda is 720kWh per person per year[19] which seems low (the UK average is 3,300kWh[29]) but this figure is actually rather inflated as it considers only grid connected consumers. Consumption of 720kWh a year is equal to 2kWh of energy a day. This figure is per person so, for an average of 4 residents in each household, the Rwandan average[30], it will equal 8kWh per household per day. There are 150 residential properties in the village so a total residential consumption of 1200kWh per day must be provided to meet the national average.

The aim of this project is for each residential home to have a service equal to that of grid a connected property. Very basic electrical devices such as lights, mobile phone chargers and fans only consume a few watts of power each so supplying only these devices would require only a small number of panels. More power intensive electrical devices such as fridges, cookers, water heaters, and televisions consume hundreds or even thousands of watts. As mentioned, the national average figures above are for grid connected Rwandans, who likely live in large cities. However this grid is primarily designed for residents who, as yet, have no energy access at all except biofuels like wood. Therefore it is very unlikely that they will have any high consumption devices, they may not have any electric devices at all. The average load shall therefore be considered to be much lower than the average of those Rwandans that are already grid connected. Three bands of consumption for an individual household shall be considered as sensitivity variables.

Band	Energy consumed per household (kWh/day)	Total energy consumed (kWh/day)	Average power (W)	Peak power (W)	Household devices
Low	0.5	75	20	76	Lights, fans, phone charger
Medium	1	150	41	152	All of above + Television
High	2	300	83	304	All of above + Refrigerator

The commercial loads have different requirements to the residential, as a whole they are consuming power more steadily and predictably throughout the day and the consumption per property is likely to be higher than the residential properties. Commercial properties here are defined as any non-residential building including schools, health centres, bars and shops. Additional public loads such as street lights and water pumps are here defined as part of the total commercial load. The commercial properties will be given a larger daily average of 5kWh per property per day, including public loads. The commercial load is higher because they are more likely to have high consumption devices but also they’re more likely to invest in electrical devices to help their business once the power is available to them. The baseline load profiles generated by HOMER are shown in figure 3.3 and 3.4. The commercial total scaled average power is 4.17kW, the peak is 11.21kW. Random variability of 10% was added both day-today and time-step-to-time-step power levels for both residential and commercial profiles. The scaled loads for a randomly selected day, July 14th, are shown in figure 3.5 and 3.6.

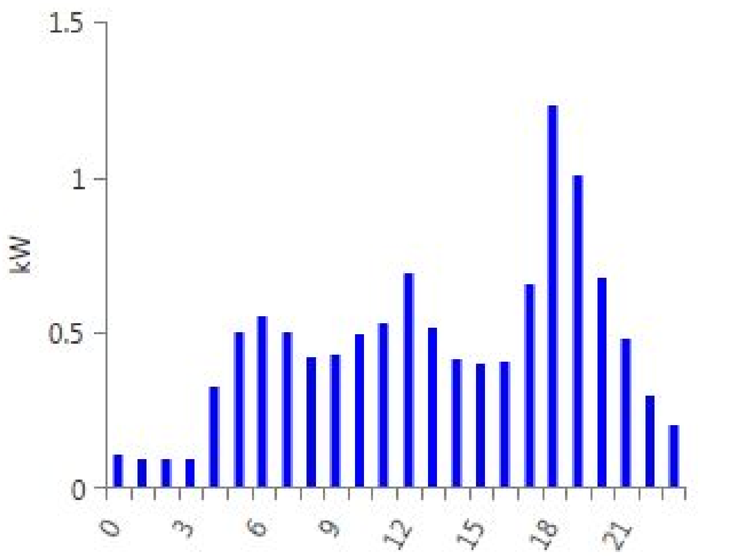


Figure 3.3: Residential load profile (baseline)

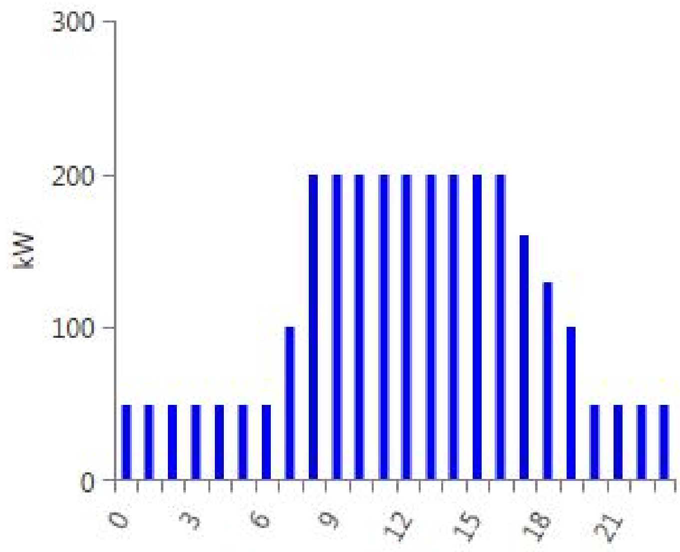


Figure 3.4: Commercial load profile (baseline)

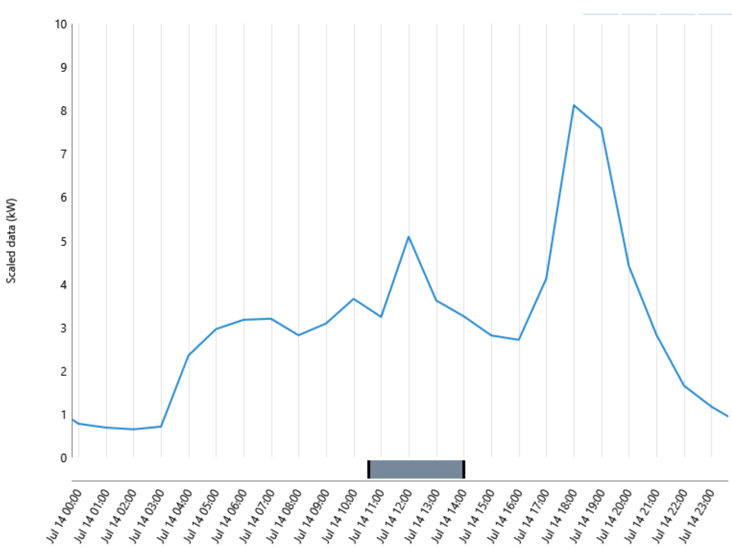


Figure 3.5: Residential load for July 14th (scaled)

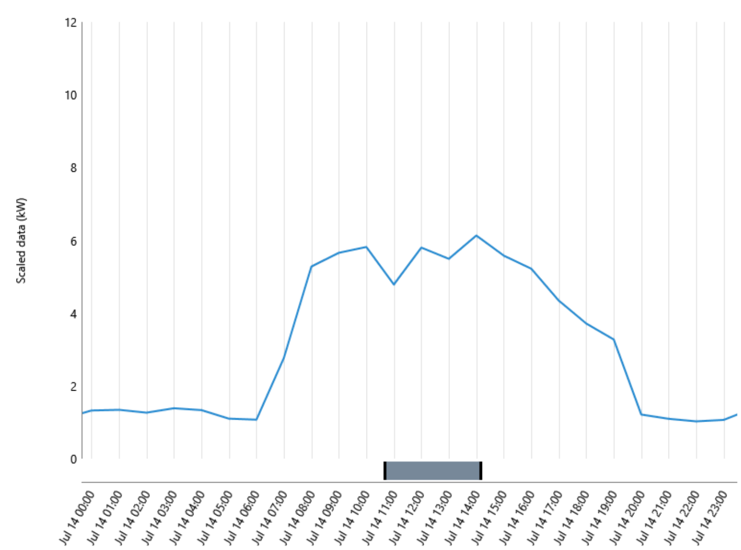


Figure 3.6: Commercial load for July 14th (scaled)

A simple measure of load and supply quality in electrical engineering is the load factor, f_{Load}. The load factor is a measure of consistency in the load profile. It is calculated by the following equation.

$$f_{Load} = \frac{Average\ load}{Maximum\ load\ for\ given\ time}$$

The maximum load for a given time is the amount of energy in kWh would be consumed if the peak load was applied for the duration of that period. A high load factor (close to 1) represents a steady load that doesn't need extra energy storage to service the peaks. As this extra storage capacity sits idle for much of the time the capacity is not utilized in a cost effective way which increases the cost of electricity. So a high load factor is desirable for a cost effective microgrid. If the load factor is too low then load shedding, which is discussed in 3.5, may be required. The load factors were calculated for the residential and commercial loads.

Residential $f_{Load} = 0.264$

Commercial: $f_{Load} = 0.34$

These numbers show that the loads are highly variable so the required storage for the microgrids will increase. The load factors also confirm the consistent commercial load profile and suggest that commercial loads may be more profitable for microgrid ventures.

3.3 Distributed Generation

Distributed generation can encompass any small scale generation of power that is not part of the main grid infrastructure. Typically DG has been used to describe renewable energy sources but diesel based generators are actually some of the most common DG units, especially in developing countries where the initial capital required for renewable generation is high. Solar radiation is abundant across the continent and solar power is the obvious choice for many rural communities in Africa. Additionally, as discussed in section 2.4 there is huge hydropower potential in Rwanda and the resource holds significant potential in the rest of Sub-Saharan Africa too, particularly Central and Eastern Africa. Hydro currently represents 45% of Sub-Saharan Africa's generation which is itself only a fraction of the total commercially exploitable potential[2]. Wind power, however, is only commercially viable for countries on the East coast of Africa. Too many Sub-Saharan countries are unable to access wind power effectively so it will not be considered viable for this project. Solar PV and hydropower generation are the two DG technologies that will be discussed here.

3.3.1 Solar

Solar PV technology converts energy from sunlight into a DC current by a process similar to that demonstrated by a photodiode. As photons hit the panel they create electron-hole pairs which carry current across the p-n junction. Each cell only produces a tiny amount of power so they are arranged in a grid to maximise total voltage drop and power output.

The three main PV technologies are Monocrystalline silicon, Multicrystalline silicon, and Thin-film silicon. They differ in the way the silicon is processed, more recently the processes have been combined to form Hybrid solar cells with the best qualities of each. As shown in [31] there are different types of solar technology in the research stage such as Multijunction cells that can reach over 40% efficiency. In reality, for commercial use the efficiency of solar panels is only around 10-20% depending on the type of cell.

The amount of solar radiation that is present on a panel at any one time is highly variable, additionally the power output is dependent on cell temperature so exact power output is complex to calculate. A simplified equation for power output is:

$$P = Yf\frac{G}{G_{STC}}$$

Y - PV rated capacity (kWp) [Output under standard test conditions]
f - PV derating factor (%) [Real world effects such as dirt, shade and ageing]
G - Solar radiation (kW/m^2)

Standard test conditions are defined as $1kW/m^2$ solar radiation (so $G_{STC}=1kW/m^2$), 25^oC cell temperature, and no wind. The output of a solar module is often specified as the output power of the module in standard test conditions (Y), measured in kilowatt peak (kWp). This equation shows that the main dependents of power output are cell efficiency, shading, and solar radiation. Shading is directly controllable by residents and routine cleaning of the panels is a key maintenance role to maintain high efficiency.

Solar is particularly well suited to Sub-Saharan Africa for a few reasons; firstly it is an inexhaustible energy resource that is in abundance near the equator. Secondly solar cells have a lifetime of over 30 years with minimum maintenance as they contain no moving parts or mechanics which also means the operational cost is virtually nothing. Finally solar power is cost linear and some studies even suggest that smaller PV systems are more cost effective than large ones[32], this makes solar ideal for microgrids and small remote communities. Some limiting factors for solar are a relatively high installation cost and low efficiency, however, capital cost is decreasing[33] and efficiency is increasing[31]. Solar may soon overcome these hurdles entirely and, by current projections, could overtake coal to become the cheapest energy form in the world.

Another solar powered tool available to the rural community is a solar water heating system (SWHS). SWHS is a method for water heating that uses heat from solar radiation and a highly conductive system of pipes or fluids. It is highly efficient electrically and economically when compared to electric heating. There is huge potential for SWHS to drastically reduce the cost of heating water, especially when deployed on a community scale. A system costs around $1500 and will pay for itself within 4 years[19] while potentially lasting over 20 years. A SWHS system will be considered for the community with the costs added to overall system costs.

To define a solar array in HOMER some inputs are required; size (kW), capital cost ($), replacement cost ($), and O&M (operation and maintenance) cost ($/yr). Capital, replacement, and O&M costs for small off-grid systems in Africa can be highly variable as demonstrated by figure 3.7. Those which include batteries show even larger variation. This can be partly explained by regional price differences, any pricing defined in this project will vary across the continent.

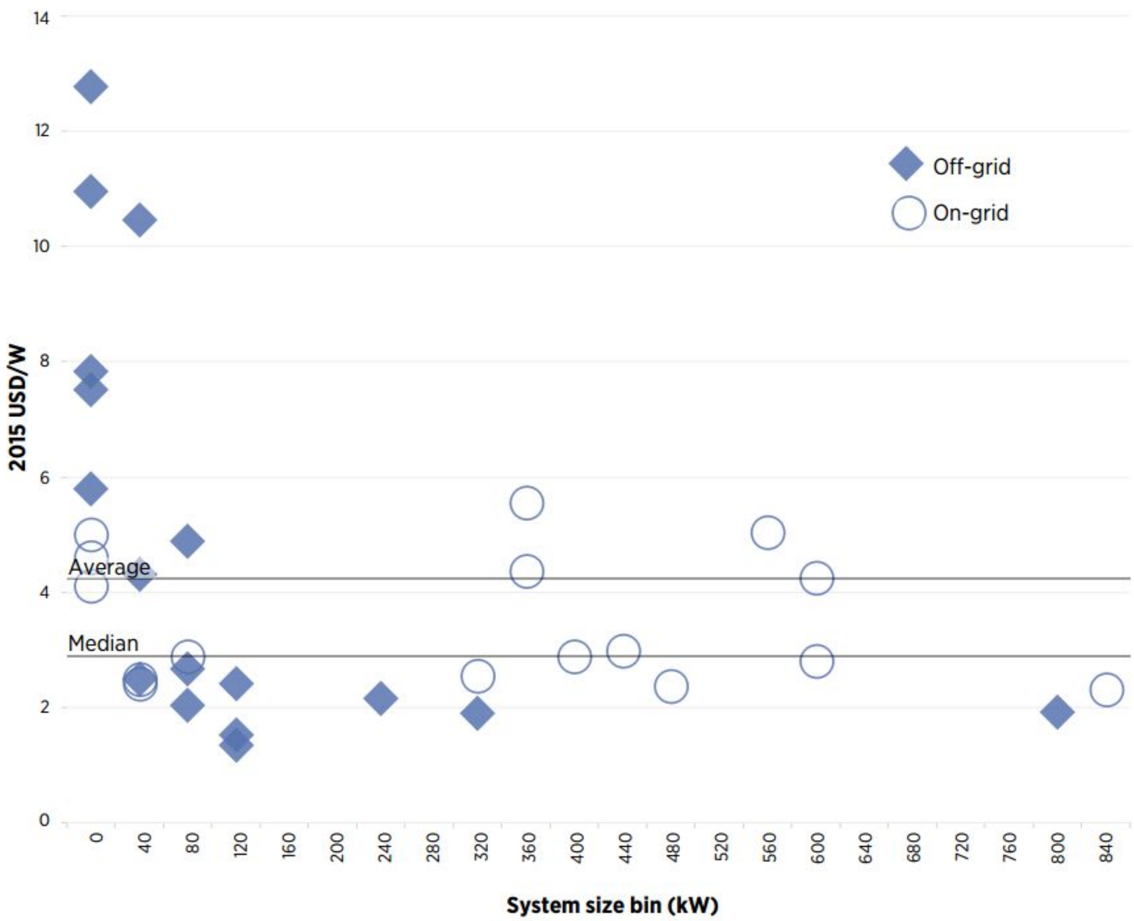


Figure 3.7: Solar microgrid costs in Africa[34]

A catalogue of solar PV models is available within HOMER but it is unclear whether any of these models are available for purchase in the study region. Instead a real model that is available for purchase in Rwanda shall be used. AIMS Power (aimscorp.net) is a vendor of microgrid equipment in Rwanda and they serve all the countries in Sub-Saharan Africa making them a suitable vendor for the product. The following table lists the key features of the PV250POLY solar panel pack that shall be used, each pack is a set of 6 individual panels.

Specification	**Value**
Size	250W x 6 = 1.5kW
Voltage	24V (each)
Capital/Replacement cost	$1720
Lifetime	30 years
Temperature coefficient of power	-0.43%/ºC
Efficiency	16.77%

The PV source is defined in HOMER by these parameters. The total size of the array is an important aspect of optimization. As with all grid components HOMER has an in built tool to optimize the size of the array so there is no need to enter explicit sizes to consider.

To define solar radiation levels for the microgrid HOMER takes location data and outputs the NREL daily solar radiation figures in kWh/m^2 and a clearness index (the fraction of radiation that reaches the earth's surface) for each day. The latitude and longitude of the real Rwandan solar microgrid, Rushonga (2^{o}9'S 30^{o}47E), are used. HOMER states a scaled annual radiation average of 5.23kWh/m^2/day and average clearness index of 0.522. Figure 3.8 displays the monthly average and maximum solar radiation for the Rushonga area. The solar exposure is relatively consistent throughout the year which is a positive indicator of the suitability of solar for the region.

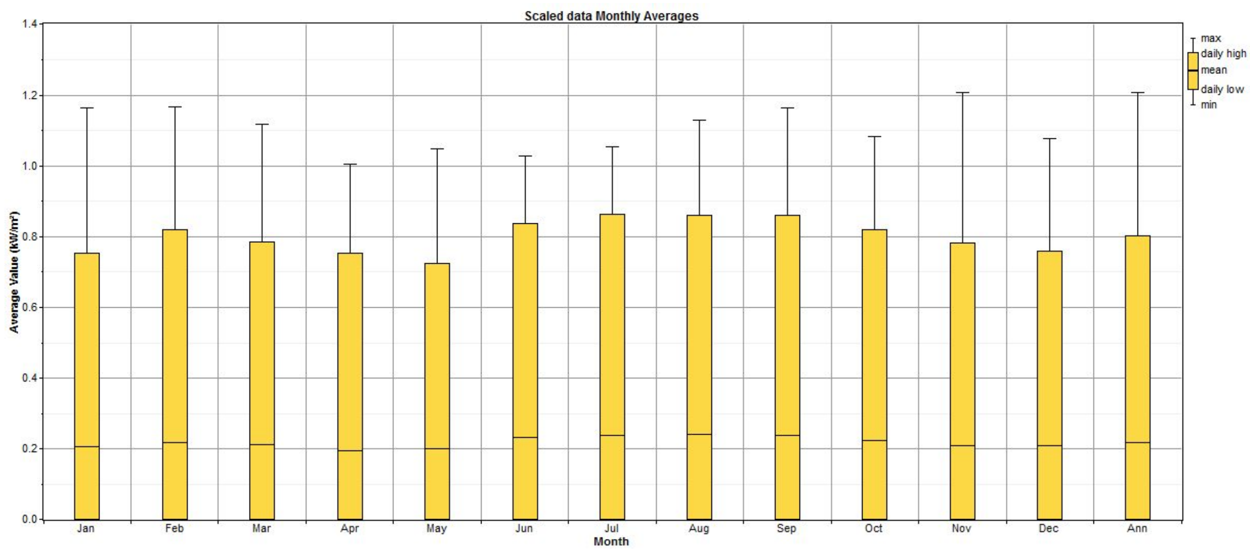


Figure 3.8: Monthly solar radiation in Rushonga, Rwanda

3.3.2 Hydro

Hydroelectric power is generated by the gravitational force acting on water, this force is converted to either AC or DC electricity by a turbine. The scale of production possible using this method varies greatly, from the world's largest power station; the Three Gorges Dam in China, to pico hydro systems that may only power a single household. The main difference between these two systems is that very small hydro generation can be achieved by 'run-of-river' meaning no dam is used. Otherwise hydro systems can be scaled to fit any size of river and power requirement.

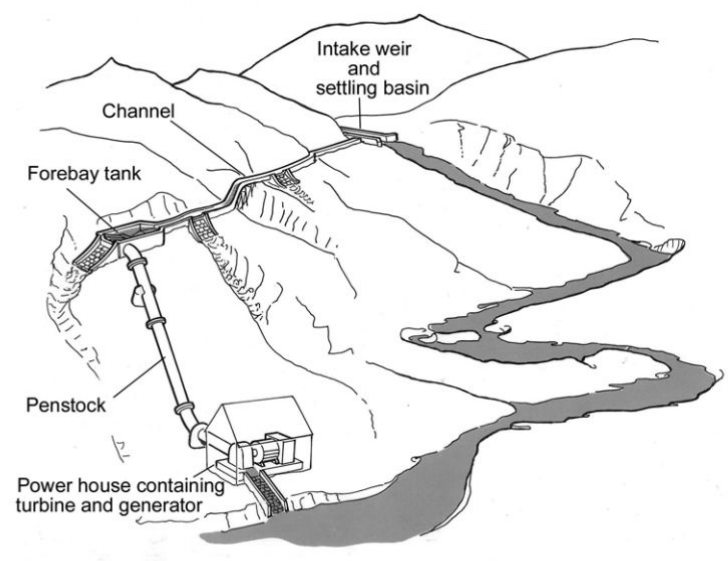


Figure 3.9: Micro hydro design[35]

A typical hydroelectric power station is shown in figure 3.9. The most common turbine in use today and the turbine assumed for this project is the Francis turbine. Francis turbines are reaction turbines that take advantage of gravitational pressure to extract high amounts of energy from the water flow. The amount of power that can be generated by a hydro powered turbine is dependent on the following equation[32]:

$$P = QH\eta\rho g$$

Q - Flow rate (m^3/s) or (0.001L/s)
H - Available head (m)
η - Efficiency
ρ - Water density (1000kg/m^3)
g - Acceleration due to gravity (9.8m/s)

The flow rate may refer to the water flow or the rate at which the turbine is at maximum efficiency. If using the water flow rate then the efficiency η must account for the lost energy from the water to turbine and also from turbine to electricity. In this project we will refer to flow rate as the turbine design rate and efficiency is that of the turbine converting to electricity only.

Other factors can affect the power output. This equation does not account for variation in river flow, the changes in flow rate can be expressed by a minimum and maximum flow ratio that is expected through the turbine. These values can be estimated from local climate measures, rainfall and yearly river flow measurements and will affect the power output accordingly. Another variable not expressed in the equation is pipe head loss. This is a proportion of the kinetic energy in the water that is lost to friction within the pipe. Pipe head loss is dependent on the flow rate and the parameters of the pipe, including diameter and internal material. All of these figures are entered into the HOMER input stage. The main variables to consider are efficiency, flow rate, and available head. The available head is the distance that the water falls vertically from intake to the turbine, this should be maximised by building the hydro station in a location with high gradients.

Cost analysis studies rate hydropower as the least cost option for microgrid applications where there is a viable resource. Hydropower is unique in the renewables presented here as it is consistent on an hourly or daily time frame. Inconsistency arises on a yearly time frame due to seasonal rainfall fluctuations, which must be addressed with any design in such an environment. As mentioned in section 2.1; Rwanda's topology is particularly well suited to small scale Hydro electric power generation but the rainfall fluctuates heavily twice yearly.

The hydro based microgrid simulated here will be similar in design to the Rubagabaga microgrid shown in figure 3.2. To compare with the solar microgrid the aim is to serve 150 residential loads and 20 commercial loads with exactly the same requirements as the solar case. A generic 50kW hydro design is used, with a reduced head of 33.1m that will lower the nominal capacity to 25kW, design flow rate is 154L/s. The flow rate of the river is significantly higher than the turbine design rate, normally the entire hydro source should be utilised but in this case only a portion of the river is assigned for the microgrid. It shall be assumed that the remaining river flow is used to power the national grid as in the Rubagabaga set up. The following are the

associated costs and parameters given for the 25kW system, sourced from HOMER and web sources[36][37]:
Capital: $80,000
Replacement: $40,000
O&M: $2,400
Lifetime: 30 years
Efficiency: 52%

A river can be defined in HOMER by creating a 'hydro source' and entering monthly river flow in litres/second. The Rubagabaga river is relatively large with an average flow rate of around 800L/s, however only a portion of this is allocated to the microgrid so the river flow input must represent this portion. The flow will be set with lows of 60L/s and highs of 220L/s. The river flow will fluctuate according to the wet and a dry seasons so the monthly flow rate figures should be curated around these changes. The monthly flow rate is illustrated in figure 3.10, the flow rate fluctuations correspond to monthly rainfall in Rwanda.

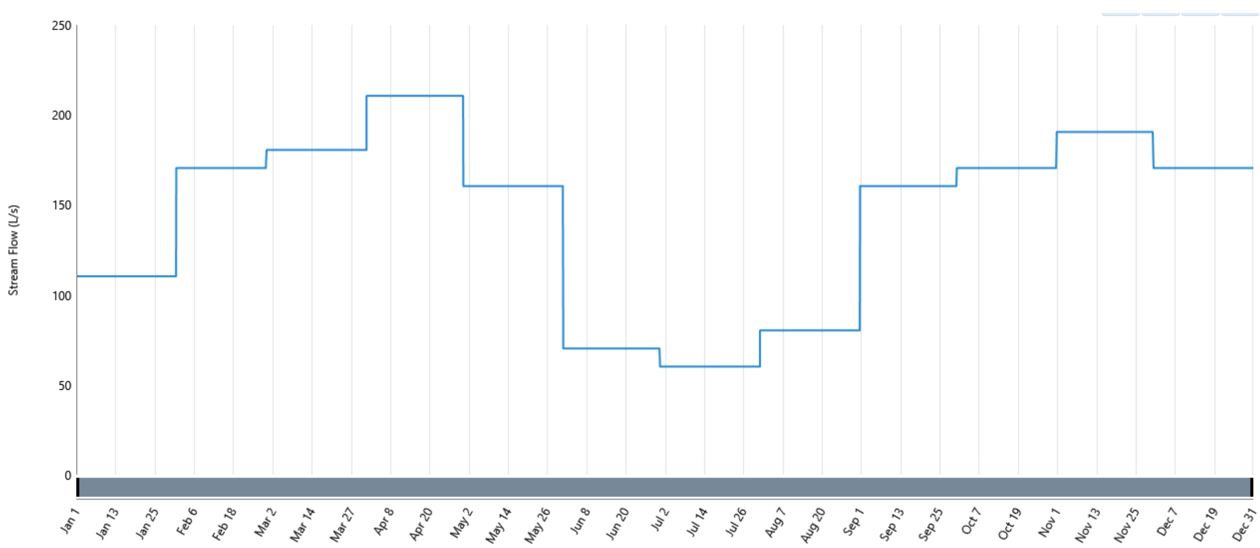


Figure 3.10: Estimated monthly flow rate for Rubagabaga river

3.4 Distributed Storage

By their nature renewable energy sources such as solar and wind are intermittent on an hourly basis which is a problem for consumers who naturally require reliable power at all times of the day. While many microgrids use synchronous generators to cover fluctuations in renewable output, here the same effect shall be achieved using storage solutions. Generators on a grid also perform other services that must be covered by the storage technology on a renewable microgrid. These can generally be split between power quality services and supply services. Power quality services ensure the grid has a stable power flow and minimal harmonic interruption. To achieve high power quality the following services must be ensured by any storage technology used.

- Voltage regulation & support
- Frequency response

A secondary service performed by generators is that of time based generation support. Generally this involves increasing and decreasing supply to the grid to deal with load peaks and increase overall efficiency. To cover supply related support a storage device must be able to perform:

- Electric energy time-shift services
- Electric supply capacity support
- Load following

Some of these services are largely based on the control scheme deployed but all require a robust and reliable storage device. Energy can be stored in many ways but only the most flexible are appropriate for a microgrid. This is because a microgrid storage device is required to charge and discharge potentially multiple times a day consistently while also provide fast acting grid support within seconds of instruction.

3.4.1 Batteries

Chemical batteries are an imperfect technology and have famously lagged behind in the otherwise rapid advancement of the electronics industry. Batteries are reliant on chemical reactions to sustain themselves and this means that there is always a trade off between power, energy, and durability. Often a battery can perform well by one of these metrics but not two, a high power battery can deliver short bursts of energy, useful for vehicular acceleration for example. A high energy battery is characterised by a long and slow discharging, this is useful for mobile phones where the user is primarily concerned with battery life. Both high power and high energy batteries will degrade with use, and the more energy drawn from them before a recharge, the faster they degrade. This metric is described by the 'depth of discharge', measured as a percentage of total capacity. An 80% depth of discharge is a deep discharge which only certain batteries can sustainably perform. External conditions such as temperature and humidity also have an effect on the durability of the battery and batteries are all guaranteed to slowly decrease in capacity and eventually die. The lifetime of a battery can be extended by decreasing the depth of discharge and implementing proper storage practices including charge control.

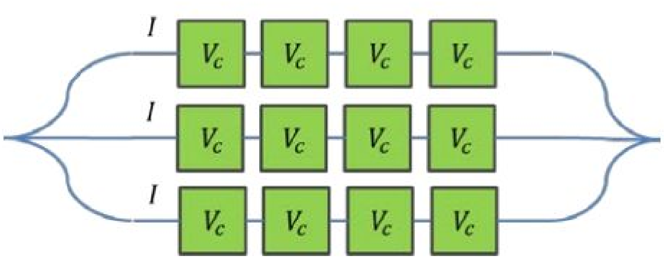


Figure 3.11: Battery bank configuration[38]

A microgrid has a high storage requirement so once the battery type is chosen then a configuration must be considered that forms a battery bank. The batteries in a bank are arranged as shown in figure 3.11. Each row is called a 'string' and the number of cells in each string determines the voltage over the bank as a whole.

The voltage and current levels over the bank are calculated by[38]:

$$V_{bank} = CV_c$$
$$I_{bank} = RI$$

The clear market leaders in proven cheap distributed storage are lead-acid and li-ion batteries. Lead-acid batteries are the oldest type of chemical electricity storage and for that reason they are low cost and easily sourced all over the world. The U.S. based Electric Power Research Institute in collaboration with the Department of Energy produced a comprehensive analysis of current storage methods [39], followed by [40]. These papers give an overview of current technologies and organise them by parameters of size (power rating), discharge time, and cost. It should be noted that these are levelised costs from the USA in 2013 but they should provide a relevant comparison nonetheless. Another reference used here is the IRENA battery storage outlook report [41]. These papers show that lead-acid batteries are currently cheaper than li-ion but that even a well managed lead-acid battery may only have a lifetime of around 3 years. If their charge level is kept above 80% at all times they may live to around 5 years but this would require a large increase in capacity and components as the discharge capacity is reduced.

Li-ion batteries can provide a longer lifetime as they degrade much more slowly than lead-acid, this means an equivalent li-ion battery system can be established with much fewer batteries each with a larger depth of discharge. They also experience decreased losses and a very high energy density meaning more energy is stored per unit volume which is why they are the primary choice for modern consumer electronics. These features additionally help li-ion batteries discharge quickly which helps in grid applications for frequency regulation. Li-ion batteries are currently more expensive than basic lead-acid batteries which has limited their exposure in African markets. As a newer technology, they benefit from rapid cost reduction in the years to come as they move into the mainstream. As figure 3.12 illustrates; the cost of li-ion batteries is already lower than advanced types of lead-acid cell and it is set to fall to the lowest of all the battery types.

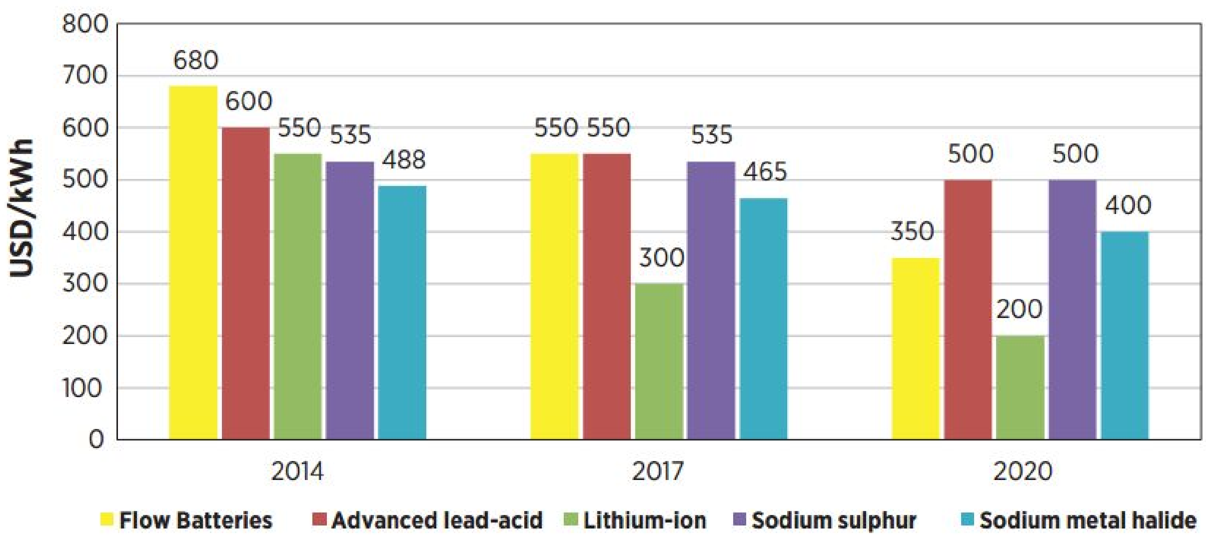


Figure 3.12: Battery price projections by type[42]

We are able to compare both the lead-acid and li-ion batteries within the HOMER size optimization tool. Within this analysis is included the scenario of none of that storage type being included. To compare one against the other therefore we just analyse the results for when one or the other battery is set to 0.

For some relative cost values the report from IRENA[41] is used, it states the following for li-ion battery costs in the region: minimum cost: 250$/kWh, maximum cost: 500$/kWh, average: 375$/kWh. Rwanda is likely to be at the higher end of that scale so a value of 400$/kwH is used for the lithium battery and 300$/kWh for the lead-acid. The following table lists the key features of each battery simulated in HOMER.

	Li-ion	**Lead-acid**
Price	$400	$300
Nominal capacity	1.02 kWh	1.03 kWh
Nominal voltage	3.7 V	2 V
Maximum capacity	276 Ah	513 Ah
Round trip losses	8%	15%
Minimum state of charge	20%	40%

3.4.2 Pumped Hydro Energy Storage

Storage of this type, assisted by large dams and reservoirs, has dominated grid scale storage in recent years representing 99% of storage in use[41]. Pumped Hydro Energy Storage (PHES) is widely considered to be the most economical long term storage solution where available. Research suggests that small scale PHES can be economically viable where existing reservoirs exist but that most cases will not be economical[44]. A PHES system will be trialled on the hydro microgrid with the expectation that it will not be economically viable. Where it is viable PHES brings many virtues including low maintenance, low cost, and freedom from carbon emissions and harmful chemicals.

A generic PHES system is available on HOMER that has a capacity of 245kWh, which is more than enough to serve the daily load. It may actually be far over the needs of the village and therefore be prohibitively expensive considering the economies of scale that accompany PHES. The initial capital cost is much higher than battery solutions as large civil works are required but the lifetime is increased and only minor replacements are needed. The following costs are given for the pumped hydro storage system.
Capital: $22,000
Replacement: $500
O&M: $2,000/year
Lifetime: 40 years

3.5 Control

The microgrid requires a significant level of control in order to ensure reliable, safe, and economic power delivery. The level of control typically deployed in a microgrid surpasses the control present in the national grid. Currently basic grid control is to increase generator output according to the load present on the system, a method called load following. Load following is not expected to be an effective dispatch strategy for a renewable based microgrid but it shall be trialled.

The microgrid diagram, figure 3.1, in section 3.1 displays some of the control points typically found in a microgrid. Namely microsource controllers (MC), load controllers (LC), and the microgrid central controller (MGCC). The controllers are often incorporated into power electronic converters which can convert from DC to AC and vice versa while performing electrical management. In both grids for this project the control will be physically present at the inverter nodes.

A distinction should be made between primary control and secondary control. Primary control is concerned with the reliability of the network, it should be fast acting and primary control strategies presented here do not require communication. Secondary control acts over a longer time frame and is included for optimization of the grid. The grid may function in a robust manner without secondary control but conditions can be vastly improved with it. For example; peak load communication, emergency load response, consumer economic incentives and coordination of primary control actions[45]. Secondary level control can be achieved by the addition of communication technologies to the system without compromising the primary control system.

The control strategies presented here are for *islanded* microgrids in particular. A fully stabilised islanded microgrid is able to connect to the wider grid and offer increased redundancy and regional stability without compromising its own system. Therefore any stable islanded microgrid may also act as a stable grid-connected microgrid but not necessarily vice versa.

To reduce the complexity and cost of the microgrid control system a method of control based on grid voltage level as presented in [45] shall be used. Voltage based control enables full grid functionality without any central control, load control, or communication infrastructure. These are all primary control methods, all the control features are present in the MC's, and they rely only on the grid conditions for instruction. This method does require a reference voltage generator for the MC's which is normally provided by the MGCC.

Relying purely on MC's for control simplifies design but the advantages of load control are lost. The goal of load control is to increase the load factor by peak shaving. Peak shaving reduces the peak load to decrease the need for purely peak serving generators and storage capacity. However the material cost of LC's such as smart meters mean they are unsuitable for this project. The hope is that the value lost from the load control will be made up by the microsource controllers.

HOMER presents two inherent controller strategies which are load following and cycle charging which are both explained in section 3.5.1. Both cycle charging and load following dispatch will be trialled on the microgrids but it is expected that neither will produce optimal outputs. Both strategies are focussed on generator operation and inverter based micro source control as described is not yet a feature of the program. For this reason the control method must be chosen manually.

3.5.1 Microsource control methods

In this project the distributed generation control performed by microsource controllers will perform the following functions, as defined by [32].

- Ensure new microsources can be added to the system without modification in the existing Microgrid configuration
- Control active and reactive power independently
- Correct system imbalances including voltage sag
- Stabilize faults

The way in which active and reactive power are controlled in a system depends on the proportion of resistive and inductive impedance on the lines and throughout the system. As current travels through an inductor magnetic forces are generated that create an opposition to changes in current. Lines that are both carrying current and separated by a distance will store energy in the form of capacitance which opposes changes in voltage. In a large grid there are high levels of voltage in order to reduce resistive losses, the transmission lines are generally long so maintain high inductance and capacitance. This results in high inductance low resistance lines.

In a microgrid however the distances are not long so the inductance is heavily reduced. Additionally the voltage level is reduced which increases the effect of resistance. So for a microgrid there is a high resistance low inductance case which requires different control capabilities than grid level control.

To understand the effect of changing from a high inductance to high resistance circuit we can refer to the power equations derived in Appendix I for active and reactive power into a line:

$$P = \frac{V_1^2}{Z}cos(\theta) - \frac{V_1V_2}{Z}cos(\theta + \delta)$$
$$Q = \frac{V_1^2}{Z}sin(\theta) - \frac{V_1V_2}{Z}sin(\theta + \delta)$$

Where the load angle δ describes the phase difference between input voltage V_1 and output V_2, referred to as the phase angle from here on. The impedance angle θ describes the properties of the grid impedance Z, defined as:

$$\theta = tan^{-1}\left(\frac{X_L - X_C}{R}\right)$$

Expanding Z to R+jX and solving gives:

$$P = \frac{V_1}{R+jX}[V_1cos(\theta) - V_2cos(\theta + \delta)]$$

$$Q = \frac{V_1}{R+jX}[V_1sin(\theta) - V_2sin(\theta + \delta)]$$

These equations generally hold true for any transmission line.

Transmission line principles

For the long distance transmission lines X>>R therefore:

$$sin(\theta) = 1,\ cos(\theta) = 0$$

$$P = \frac{V_1}{X} sin(\delta)$$

$$Q = \frac{V_1}{X}[V_1 - V_2 cos(\delta)]$$

These equations show that active power P can be controlled by phase angle δ, reactive power Q by the supply voltage V_1, and frequency is just the product of generator torque. This is the basis of how active and reactive power are controlled on almost all grid lines and systems, it may also be required in a microgrid if the DG units are far away from the main microgrid.

Frequency droop control

Inductive lines must use frequency or P/f droop control for balancing power, particularly after system changes. Often synchronous generators are used to implement the changes in the grid. Generators are relatively easy to control and they maintain inertia which opposes changes in output power and stabilizes the grid during load changes. The method of drooping can be understood by examining figure 3.13. For some change in voltage phase angle, power, or frequency for example from $P_{01}P_{02}$ to $P_{11}P_{12}$ the frequency remains common and it's the load sharing that changes. Droop control is very common and almost all methods are based on restricting the response of one parameter to a second dependent parameter. The two parameters are seen in the name of each droop control method.

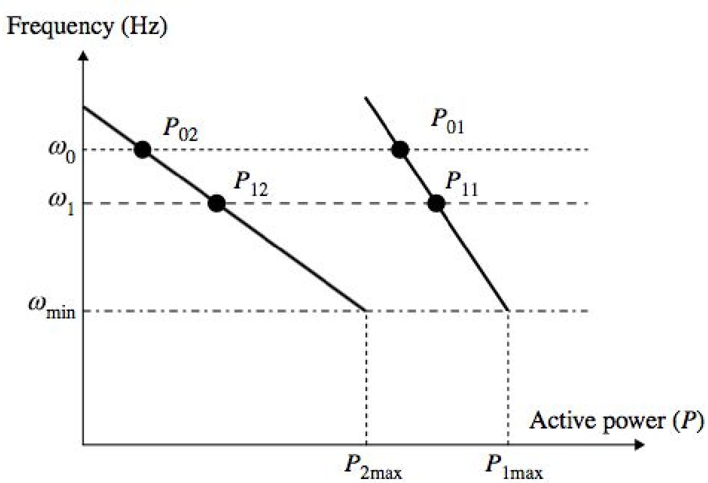


Figure 3.13: P/f droop characteristic[32]

Load following

The typical inductive generator based grid is where load following is usually deployed. This strategy essentially instructs the generators to always increase and decrease output according to the demand of the primary load. Operation of the battery bank and deferrable loads is assigned to the renewable sources. HOMER implements the load following strategy using economic analysis to serve the primary load and operating reserve at least cost. Clearly this dispatch strategy is inappropriate for a grid without generators so the expectation is that the load following simulations will experience high inefficiency.

Cycle charging

This dispatch strategy is similar to load following in that generators are set to respond to unmet primary load. Instead of just covering the load required cycle charging orders the generators to run at full capacity and direct any additional power to the deferrable loads or the battery bank. Normally cycle charging is optimal for systems with little or no renewable power to serve these secondary loads but here it may be used as a moderation of load following. For the microgrids in this project cycle charging will act to maximize renewable output and storage charge at all times. This is slightly more useful than load following but not ideal, the following strategies are more suited to the microgrid structure and components.

Microgrid control principles
For a microgrid generally the resistance is likely to dominate the inductance so R>>X. This changes the composition of the basic power equations which means different control schemes are needed. Additionally in the microgrids presented for this project there are no synchronous generators so power stabilization must be achieved without inertia or by simulated inertia. From the original equations, reactance can be neglected and phase angle δ is small so we can deduce the following relationships:

$$sin(\theta) = 0,\ cos(\theta) = 1$$

$$P = \frac{V_1}{R}[V_1 - V_2 cos(\delta)]$$
$$Q = -\frac{V_1 V_2}{R}\delta$$

These equations show that, given a small phase angle δ and voltage difference ($V_1 - V_2$) , the phase angle δ is dependent mostly on reactive power Q and the voltage difference V is dependent mostly on active power P.

Reversed droop control
This control method is a voltage based control strategy that is based entirely on the voltage level across the microgrid. This method is highly efficient as both generating units and loads can respond reliably without the need for inter communication. In the case of the microgrid where R>>X, there is a linkage between voltage level and active power in the system. This means P/f droop control is not possible and therefore P/V or 'reversed' droop control should be implemented.

The P/V droop controller requires three individual droop controllers; Q/f, V_g/V_{dc}, and P/V_g. The V_g/V_{dc} controller takes DC voltage from a DG unit and determines a reference grid voltage V_g. This is combined with the frequency from the Q/f controller to determine the voltage level for the inverter. The P/V_g droop controller determines the power P_g and the droop characteristic can be specifically tailored to the DG source to maximise power output.

Reversed droop control is discussed fully in [46], [47] and [48]. As we are operating the grid in islanded mode the grid is unable to obtain reference values of voltage and frequency from the main grid. Therefore reference signals must be internally generated. Research papers such as [47] suggest that an inverter based storage device such as a battery is most appropriate for maintaining reference levels in islanding mode.

Maximum power point tracking
For solar panels there are two control methods commonly used, pulse width modulation (PWM), and maximum power point tracking (MPPT). All panels output power with particular levels of current and voltage which vary according to the I-V curve of the panel. Both methods must consolidate the solar output voltage and the DC bus voltage level. PWM drops the solar output voltage to that of the battery bank which is simple but reduces output power. The MPPT controls

the solar panel in a way that the output voltage matches the DC bus and power output is always maximum. The maximum power point is a highest voltage possible for each current band on the panels I-V curve and MPPT is the act of applying appropriate resistance in order to get that maximum output power. MPPT systems have an increased efficiency and perform particularly well for larger solar arrays where the battery autonomy is a day or less. MPPT will be very well suited to the microgrids in this project so shall be trialled. HOMER is able to explicitly model an MPPT for the solar array the effects of which are explained in the results analysis.

Prime mover speed control
The hydropower turbine has a variable rotational speed that can cause power imbalances. The speed controller will alter the rotational speed of the turbine to fix power imbalances and ensure maximum efficiency. Unfortunately this control method is absent from HOMER but it should be assumed incorporated in the final design.

3.5.2 Inverters

Solar PV and batteries both operate on a DC voltage bus, and depending on the type of station hydro can produce DC too. Our aim is to supply an AC microgrid network so that consumers can use power exactly the same as if they were grid connected and so that the microgrid is ready for interconnection in the future. To consolidate these two power types we use a converter, more specifically in this grid we mostly use *inverters* that can convert a DC input to an AC output. The inverter should be positioned in between the DC supply bus and the AC load bus.

The basic function of an inverter is the transfer of a DC voltage level to an AC signal as close to a sine wave as possible. Modern inverter topologies are highly complex but most are based on the simple H-bridge shown in figure 3.14. This design gives a basic 3 level output (-E, 0, +E) and allows for both inverting and rectifying.

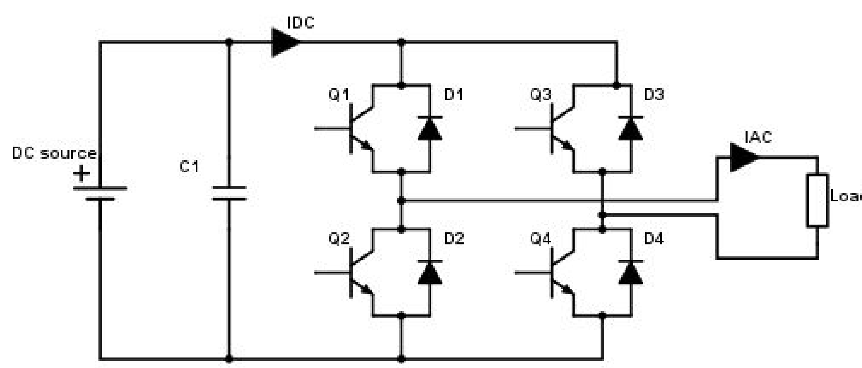


Figure 3.14: Single phase H-Bridge inverter

The transistors Q1-4 act as switches that can be activated to change the polarity and direction of both V_{AC} and I_{DC}. The polarity of each of these variables at any point in time dictates the direction of power flow so that both DC-AC and AC-DC conversion can be achieved. For example gating Q2 and Q3 will create a negative V_{AC} at output as Q3 is higher than Q2. As long as V_{AC} maintains a voltage then the direction of power flow is dependent on the direction of I_{DC}. In this case I_{DC} will remain positive as it can flow down through Q3, this means the direction of conversion will be DC to AC in this configuration. As mentioned this design can only achieve a 3 level output so alterations must be performed to generate a more sine like wave.

Pulse width modulation (PWM), the same as used for solar PV control, has been described as the foundation of control in power electronics[49]. It allows the inverter to increase the number of voltage levels and implement vital control techniques. PWM is a modulation technique that translates the voltage level of the signal at any point in time into a width between two square wave pulses. The simplest implementation of PWM is by natural sampling using comparators to compare a sine wave to a triangle wave carrier. Any time step where the sine wave voltage level is greater than the carrier is a 1 and any time step where it is less is 0. This creates a pulse square wave with each pulse separated by sinusoidally changing lengths of time. For acceptable performance carrier frequency must be at least ten times the sine wave frequency, which can create distortion in the signal. The PWM signal can be considered as the sum of an infinite number of sines and cosines at varying amplitude and frequency[50]. Using Fourier series analysis allows a control system to create a single mathematical expression to describe the waveform and the harmonics. PWM is so effective because, despite the carrier distortion, the associated power loss is very low. This is due to the high switching speeds of PWM which limit the power dissipated by each transistor.

The size of the inverter indicates the level of voltage that it is able to invert without clipping. For solar applications it is now common practise to under-size inverters purposely to cause clipping in the middle of the day when output is at peak. Limiting the output of the inverter has benefits that can outweigh the loss in mid-day output as the output is increased for lower levels of solar radiation in the morning and evening. For this project a broad range of inverter sizes and prices will be compared for optimization.

The inverter in HOMER can be selected from a list much like the PV model. For the moment a generic system converter will be used. AIMS Power stocks pure sine wave inverters that give a good idea of the price for difference inverter sizes. The models on the website show that there is significant economy of scale with inverters, unlike solar panels which are highly linear in price. HOMER can use this data to create an accurate cost curve which is a key input for the size optimization.

4 Simulation

Both solar and hydro based microgrids will be simulated in a computer program called HOMER. HOMER is a leading grid simulation program designed by NREL, it takes general grid parameters as inputs and outputs an optimal least cost system based on the constraints defined. For figures that are not definitive there is an option to define 'sensitivity variables', HOMER will simulate the operation for all of the sensitivity options and give the optimal system for each scenario. This allows the user to see the effect of each variable and it will be used here for values that are subject to change or to compare load types. The functionality of HOMER is fully described in Appendix II.

4.1 Solar based microgrid

A microgrid based on solar PV generation is designed according to the technologies and constraints presented in section 3. Specifically the microgrid consists of a solar PV, either an li-ion or lead-acid battery bank, power electronic inverters utilizing reversed droop control and maximum power point tracking via unipolar PWM, and both residential and commercial loads in bands as previously described. The grid set up as viewed in HOMER is shown in figure 4.1, the additional project parameters are detailed in Appendix II.

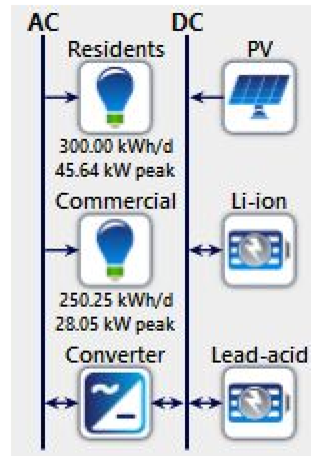


Figure 4.1: Solar based microgrid diagram in HOMER

4.1.1 Results

The results from a HOMER simulation are presented initially as a list of sensitivity cases, in this case these are the different load bands low, medium, and high from section 3.2. Selecting one case then brings the optimization results for that sensitivity case. The optimization results are variations of the grid based on the size of each component, this is where two similar components such as the two batteries can be compared for cost. A single optimization result can be selected for simulation results which include much more detailed information about the operation of the grid under those particular conditions. The following are some key results from the simulation results for the most optimal grid in each consumption band. More in depth results for each band are presented in Appendix III and analysis of all results will be presented in section 4.3.

Band	Optimal Storage	COE ($/kWh)	NPC ($)	Annualised cost per person ($/year)	Excess energy (%)	Unmet load (%)	Grid parity distance (km)
Low	Li-ion	0.257	201,945	25.11	31.8	8.1	4.29
Medium	Li-ion	0.252	283,131	35.20	23.2	8.2	0.56
High	Li-ion	0.251	452,058	56.21	23.6	7.9	0.86

4.2 Hydro based microgrid

The hydropower based microgrid will use much of the same equipment and assumptions as the solar microgrid. The specific components are a 25kW hydropower turbine, either li-ion batteries or PHES, an inverter encompassing reversed droop control and prime mover speed control via unipolar PWM, and the generic residential and commercial loads of varying levels. The grid design as presented in HOMER is shown in figure 4.2.

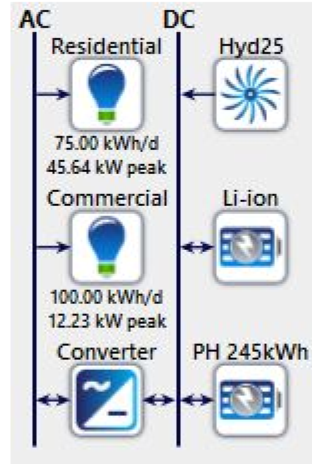


Figure 4.2: Hydro based microgrid design in HOMER

4.2.1 Results

As with the solar microgrid further results for each band are presented in Appendix III.

Band	Optimal Storage	NPC ($)	COE ($/kWh)	Annualised cost per person ($/year)	Excess energy (%)	Unmet load (%)	Grid parity distance (km)
Low	None	152,632	0.190	19.04	61.7	5.9	2.34
Medium	Li-ion	172,622	0.152	21.46	46	7.4	-3.84
High	PHES	1,581,945	0.884	196.70	11.9	8.6	45.79

4.3 Analysis of results

Analysis of the results from both the literature review and the HOMER grid simulations shall be presented to explain the grid behaviour and suggest further improvements. The electrical and economic performance of each grid type for each consumption band will be analysed followed by a comparison of storage technologies simulated and analysis of the control schemes deployed by HOMER.

4.3.1 Electrical performance

The electrical performance of each grid is determined by the total power generated, total consumed, and the effectiveness of the system to align these two. Any electricity that is generated but cannot be stored by the batteries is excess, any electricity that is required by the load but cannot be served as the batteries are empty is unmet load. This can be visualised by figure 4.3 which shows the battery charge state for the low band solar microgrid. The Y-axis is the time of day (from 00:00 at the bottom up to 24:00) and the X-axis is the day of the year (from

01/01 at the left most side to 31/12 on the right). The lighter regions are higher levels of stored energy and darker levels are when the batteries are more depleted.

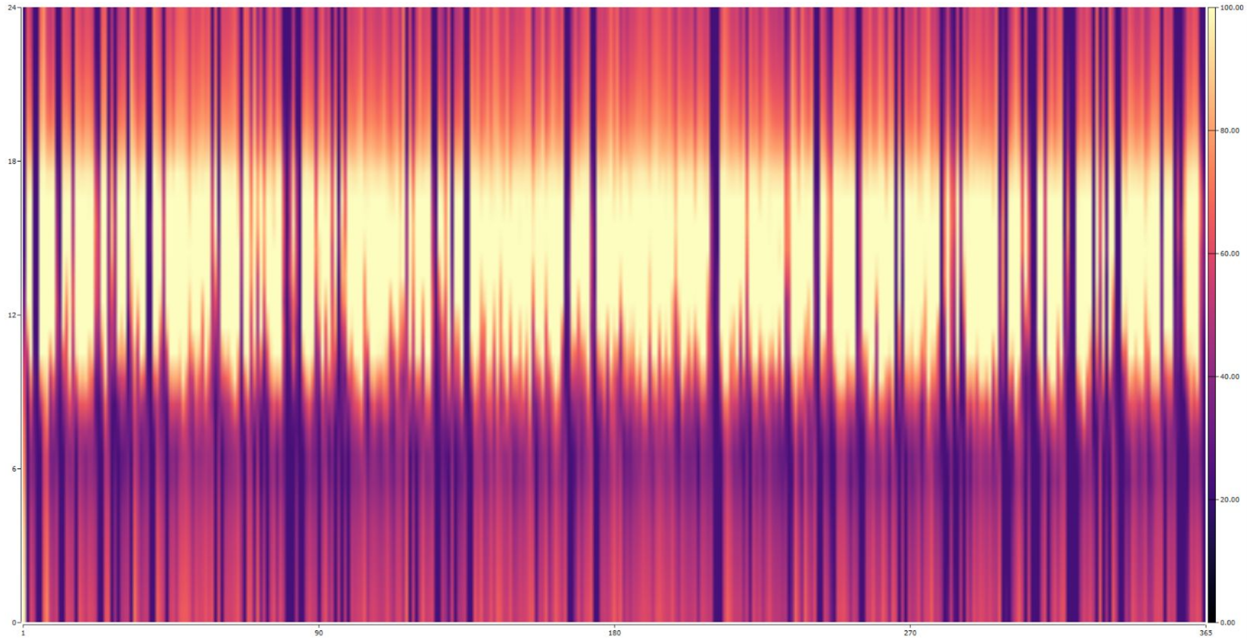


Figure 4.3: Low band solar battery state of charge over 1 year

It can be seen that the batteries hold full charge on most afternoons so cannot take on any more from the panels on those days, this is the time that contributes to excess electricity. The unmet load is shown by the dark vertical lines that are days with little or no solar radiation where the batteries are unable to charge at all. Both excess energy and unmet load are products of inefficiency and should be minimised but often the lowest cost solution will include an element of both. For both microgrids it is inevitable that excess energy and unmet load will vary hourly and seasonally depending on specific consumption habits, the following is a summary of causes and solutions.

Solar microgrid

Both excess energy generated and unmet load in the solar microgrid are independent of size, which is due to the solar PV panels and batteries being highly linear in performance. A higher band of consumption could use less panels and more batteries to reduce excess energy and unmet load but this is not the most economic solution to serve the community. The disproportion of battery storage and PV output can be visualised by figure 4.4, where the tall turquoise peaks are the battery state of charge and the shorter yellow peaks are the PV output.

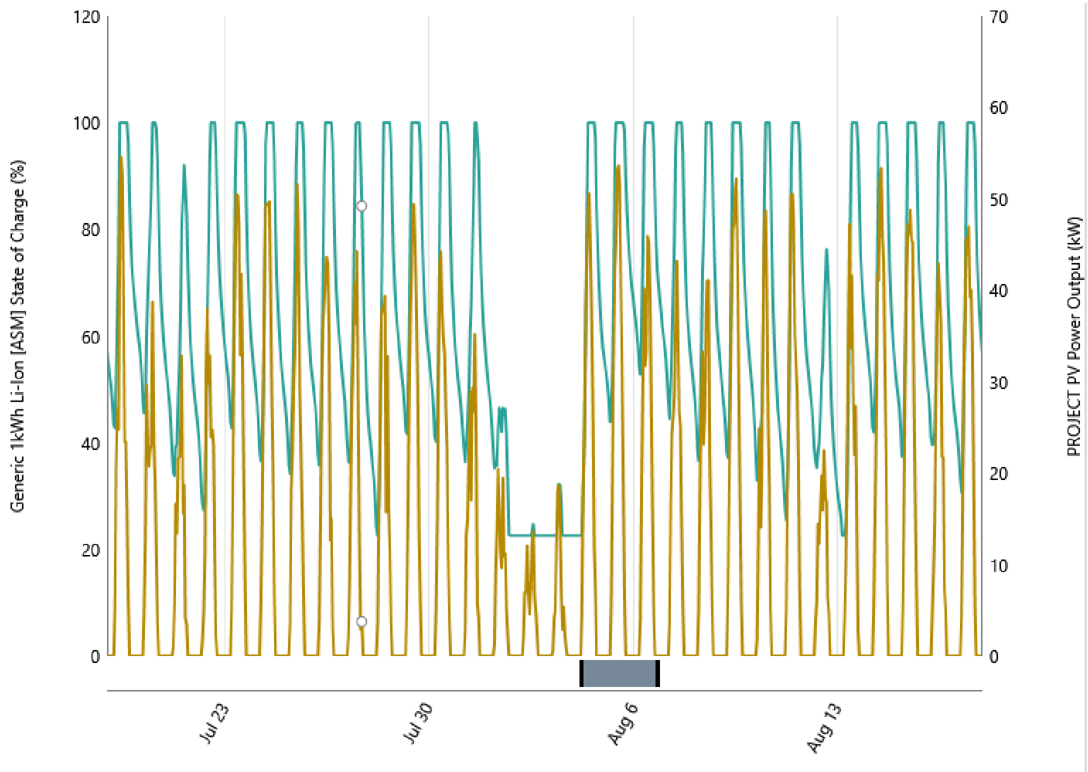


Figure 4.4: Battery state of charge and PV power output over time

On sunny days the batteries are filled quickly and the extra capacity generated by the panels is wasted. On non sunny days the batteries are depleted quickly and unable to recharge at all which results in unmet load. Excess energy is not ideal but it has no real negative effect on the power supply, unmet load however results in power shortages that can last for hours or days.

For this community it was decided that up to 10% of the load could go unmet throughout the year. As figure 4.4 shows the renewable source is sporadic meaning unmet load can be spread over a number of days. As unmet load is reduced more storage capacity is needed per percentage reduction. For example to reduce unmet load to 0% would require storage capacity that can cover three full days in August and are then unused for most of the remainder of the year. As the cost of storage in the solar microgrid is linearly related to size; the unmet load will be accepted as a cost reduction strategy.

Hydro microgrid

The excess energy and unmet load of the hydro microgrid is highly dependent on consumption level. The high band has excess electricity of 11.9% and unmet load of 8.6%, the low band however has an excess of 61.7% and unmet load of 5.9%. The three band consumption model is slightly flawed for the hydro system as the size of the turbine is 25kW for all three. The oversized turbine can explain the high excess energy for the low and medium bands. The unmet load is more constant and dependent on the seasonal rainfall variation as shown by figure 4.5, a graph of turbine output (orange, on top) and unmet load (green, below) throughout the year for the low band grid. There is a clear spike in unmet load during the dry months in June, July, and August showing clear summer power shortages. The capacity problem stated above is even more prevalent here where 0% unmet load would require storage that can cover three whole months of consumption.

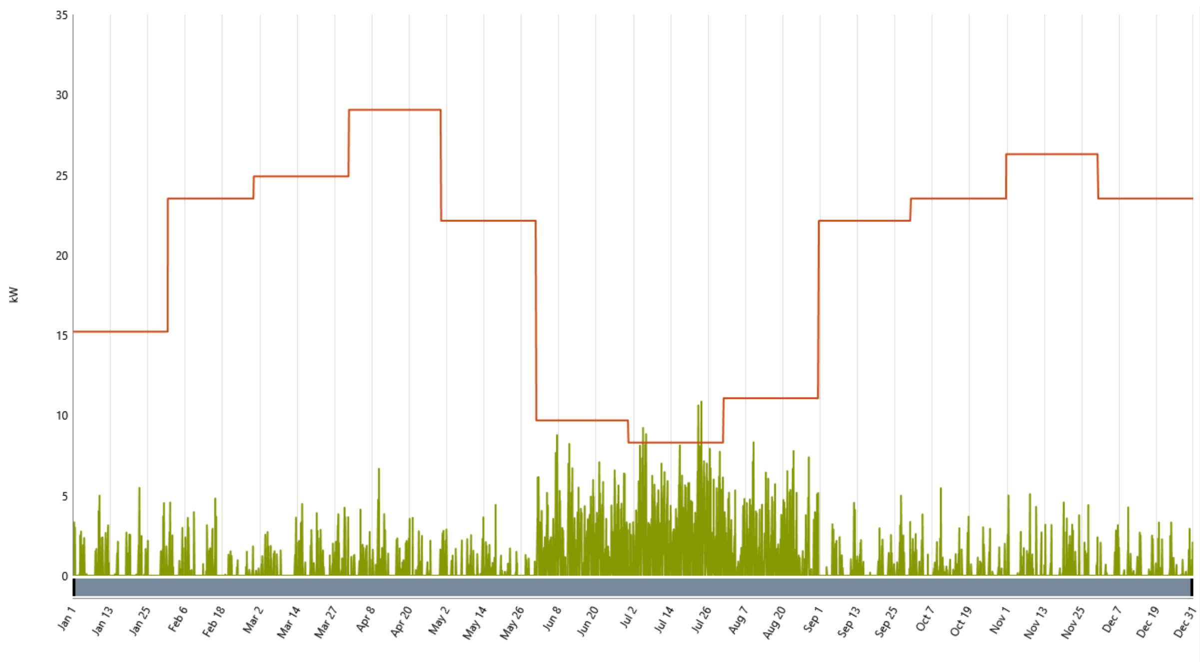


Figure 4.5: Yearly hydro output and unmet load of low band microgrid

4.3.2 Economic performance

Comparing both microgrids the results show that a microgrid based on a hydropower source is more economical in terms of both annualised and net present costs. Electrical and economic efficiency of a generator can be measured by capacity factor, which is analogous to load factor. It is calculated as follows.

$$f_{Capacity} = \frac{Average\ power\ output}{Nominal\ capacity}$$

Solar: $f_{Capacity}$ = 13.11%
Hydro: $f_{Capacity}$ = 79.57%

This tells us that the hydro turbine is working much closer to it's capacity (maximum output) for most of the time, the solar output is far below its capacity for most of the time. This inefficiency of the PV system is related to the load factor calculated in section 3.2 which is also low. However the combination of low capacity factor and the requirement of large numbers of both PV panels and li-ion batteries for the solar based microgrid mean it is overall a more costly option.

Ideally the microgrid should be commercially viable without requiring additional charity, for a cost feasibility analysis we can examine the average energy expenditure and wages in the region.

World bank data shows Rwandans spend, on average, 4.72% of their wages on energy[51]. Median wages in Rwanda are 450RWF ($0.5) per hour, the lower quartile average is around 150RWF ($0.18) per hour[30]. As agriculture is one of the higher earning professions at 667RWF ($0.81) per hour then rural farming communities may actually have more to spend on electricity. This means a median wage earner working 40 hours a week will earn $1080 in a year. By the current average they would pay $1080 \times 0.0472 = \$49.09$ for a years energy.

The prices in NPC, annualised, and per kWh for the cheapest optimization of each consumption band and grid type are shown below. The costs broken down by component are presented in Appendix III.

Grid	Band	NPC ($)	Annual cost per person ($/year)	COE ($/kWh)
Solar	Low	201,945.33	25.11	0.257
	Medium	283,131.10	35.20	0.252
	High	452,058.28	56.21	0.251
Hydro	Low	153,095.86	19.04	0.19
	Medium	172,621.74	21.46	0.152
	High	1,581,944.99	196.70	0.884

Comparing the annual cost per person for each grid to the average earner spending it can be shown that the cost of energy from the low and level band microgrids is lower. This is a subjective result but it displays a level economic competitiveness for the microgrids. The high band hydro costs are inflated due to the use of a PHES system in that topology.

Another point from this table is the reducing COE for solar microgrid users as consumption increases, a product of fixed system costs. Fixed system costs are all civil works, legal, transportation, and wiring costs along with any other vital system work. As discussed the prices of key renewable technologies such as solar PV panels and lithium-ion batteries are decreasing year on year, however the fixed costs generally do not and have not decreased. This means that fixed system costs are becoming more vital to economic assessments of a microgrid and this is bad news for low level consumers who will experience an increased COE. Figure 4.6 shows a simple graph of variation in COE with consumption level, the real values from the solar microgrid are plotted (solid) along with the predicted exponential curve of COE for levels of consumption (dashed).

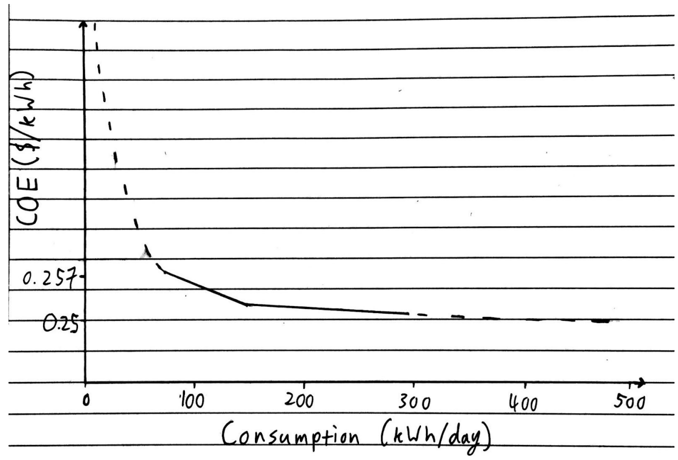


Figure 4.6: Variation of COE with daily consumption

The cost of electricity will rapidly increase for very low level consumers due to unavoidable fixed costs. The main utility grid in Rwanda has a tariff charge of $0.11/kWh for the first 15kWh/month[52] so for some communities it may be cheaper to extend the national grid and pay this reduced rate. Extending the national grid should also be considered for all cases as a grid connection in the future can be beneficial as excess electricity can be sold to the utility, generating income for the community.

The price of extending a transmission line is proportional to the distance of extension so grid connection becomes more expensive the further one is from the existing grid line. HOMER calculates the breakeven grid extension distance, which is the distance from an existing national grid line that a community must be for the microgrid to be cheaper than a grid extension. As mentioned, for lower consumers Rwanda's electricity charge is lower per kWh This lower tariff applies only to the low band. Both medium and high band will have to pay the higher tariff of $0.22 over 15kWh/month if they are connected to the main grid. The results are as follows.

Band	Solar	Hydro
Low	4.29km	2.34km
Medium	0.56km	-3.84km
High	0.86km	45.79km

These results show that a community living just a short distance from the main grid will still experience cheaper electricity with the microgrid topologies presented. The specific results are unexpected and some explanation of these values is required. For the solar microgrid it appears that the decreased tariff for low band customers has outweighed the grid extension costs to increase grid area. Medium and high band are also paying this tariff for their first 15kWh/month which is not accounted for in the model so their distance is likely to be a few kilometres higher than presented. The hydro microgrid shows vastly different results. The medium band has a negative distance which implies that a grid extension would never be cheaper than a hydro microgrid for these consumers. As with the first case the medium and high bands have an artificially high grid tariff so their distances should be higher than presented. The high band hydro system price can be considered an anomaly due to the expensive PHES system used.

From a regulatory point of view these results could be disputed as the lower tariff of \$0.11/kWh is a subsidised cost rather than a raw cost of energy. The subsidised costing is determined by the regulator and not necessarily reflective of true cost whereas the microgrid costs that are being compared are true system costs. The grid extension results therefore should be taken as an indicator of costs directly experienced by the consumer rather than absolute system costs.
A subsidised costing scheme could equally be used within the microgrid system and tiered payment schemes are common for projects of this type. Currently the most common financing scheme for microgrids in Rwanda is the private sector participation (PSP) scheme. PSP encourages private sector financing with technical, legal, and financial support from central government. It has been shown that in reality almost all projects in Rwanda have been fully publicly funded and that, in the right conditions, 'micro-hydro projects can and will be taken up by local investors' which are then 'requiring only limited external funds'[53].

4.3.3 Storage options

In the solar microgrid the storage options simulated were lead-acid batteries and li-ion batteries. The results conclusively showed that the li-ion batteries outperformed the lead-acid batteries in efficiency and cost in all three bands and configurations. This is due partly to the increased number of lead-acid batteries that is needed to achieve the same storage level compared to li-ion. The comparison table from section 3.4.1 shows that, while lead-acid batteries are \$300 to li-ion's \$400 their minimum state of charge is only 40% whereas li-ion can discharge to 20%. This actually means their cost per usable capacity is equal as shown below.

$$\text{Lead-acid: } \frac{Cost}{Usable\ capacity} = \frac{300}{0.6\times1.03kWh} = 500\$/kWh$$

$$\text{Li-ion: } \frac{Cost}{Usable\ capacity} = \frac{400}{0.8\times1.02kWh} = 500\$/kWh$$

So the enhanced performance of the li-ion battery cannot be completely explained by the minimum state of charge. The real distinction between the two battery types is due to the round trip losses which are 15% and 8% for lead-acid and li-ion respectively. Reduced losses in the li-ion mean it is immediately more cost effective than the lead-acid battery. Even with the lower losses and minimum discharge a large number of li-ion batteries are used; 132 are required for the low band and 348 for the high band. The batteries therefore represent a significant proportion of the cost for the solar microgrid, especially compared to the more consistent hydro microgrid.

The hydro microgrid had varying results on storage depending on consumption band. The low band does not require any storage at all to function normally. As explained for the high excess electricity figure, the turbine is oversized for the low band microgrid which results in the lack of storage requirements. The low consumption community would theoretically be able to access reliable energy from this turbine without any of the complexity and cost of a PHES or battery storage system.

The medium and high bands require storage in order to supply the load in the dry months of summer. Any storage technology used for these bands is idle for most of the year. Figure 4.7 shows the unmet load, hydro output, and PHES state of charge (blue, on top) vary through the year for the high band. This graph shows how the unmet load is concentrated in summer and this is the only time that the PHES system is properly utilized. If the conditions already exist for a cheap PHES installation then this idle time may not be an issue but for a commercial project the utilization of storage in the hydro microgrid is inefficient. The results are similar for an li-ion battery storage system.

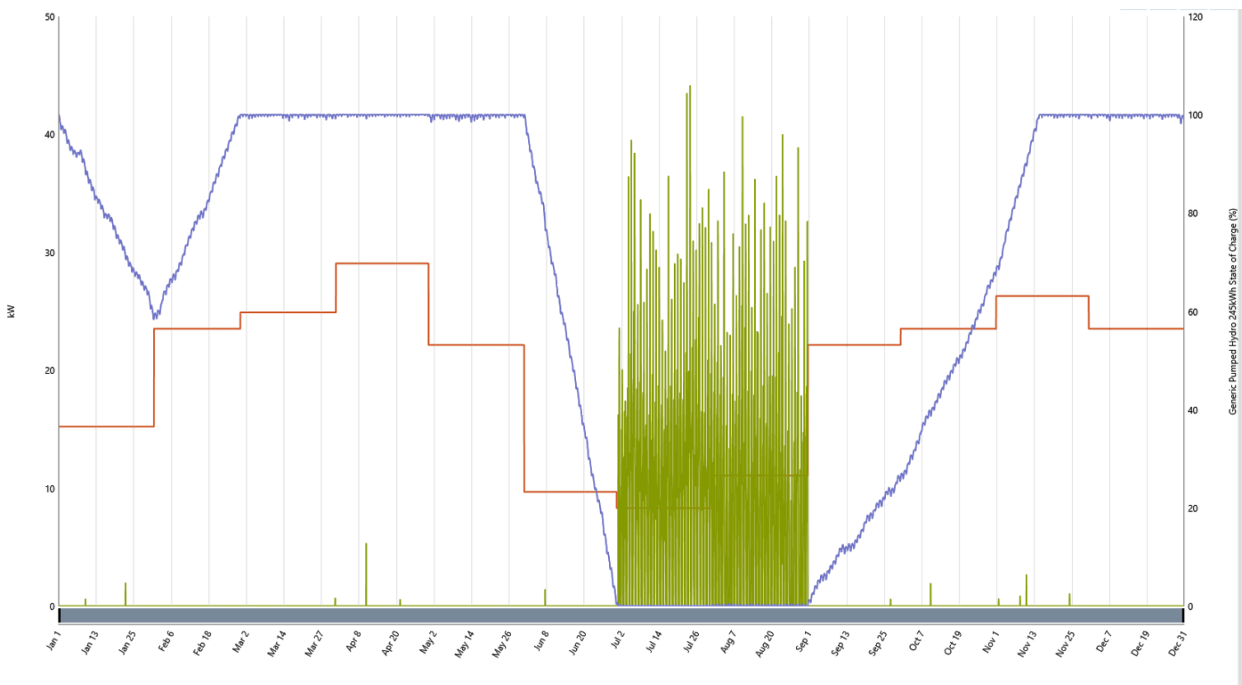


Figure 4.7: PHES state of charge over time for high band load

One hypothesis of this project was that a hybrid solar and hydro system may be particularly efficient for Rwanda where hydro resources are proven. This is because peak seasonal solar radiation and peak seasonal rainfall fall at opposite times of the year. Therefore the summer unmet load seen in figure 4.5 and 4.7 could be reduced by the introduction of a solar array to the hydro microgrid. An initial simulation was performed of the hydro microgrid with solar PV components and no storage. Results of this simulation suggest that this set up is only viable for the medium band. Even in that case the peak solar output is not enough to drastically reduce unmet load, the li-ion setup has unmet load of 7.4% which is reduced to 6.6% for the solar hydro setup.

4.3.4 Control

The results from HOMER show that, between load following and cycle charging, cycle charging is the preferred dispatch method. However many of the smart control techniques covered here are not included in HOMER. Both microgrids are simulated with cycle charging dispatch and the solar microgrid is able to utilise MPPT. The effects of other control methods, namely reversed droop characteristic control and prime mover speed control, cannot be quantified but they will be highly recommended. The simulation of microgrids with advanced control techniques by the HOMER Pro Matlab link will be suggested for future work.

5 Conclusion

This project presented the challenge of adapting and developing power grid structures to suit the conditions of the energy poor in Sub-Saharan Africa. The aims and objectives were largely met with the formation of two functional, sustainable, & economic microgrid designs. The features of Sub-Saharan Africa and Rwanda were studied to analyse the needs of the rural population in terms of energy. Key electrical components were then introduced and two grid designs based on solar and hydro power were created in HOMER for simulation. The main aims and objectives for the grids were:

I. Serve a village sized community with variable energy requirements
II. Achieve a low cost that is in line with regional income
III. Achieve a stable supply with high efficiency and power quality
IV. Analysis and selection of optimal storage solution
V. Analysis and selection of optimal control and dispatch methods
VI. Minimal carbon dioxide emissions

The microgrids created generally meet the requirements of objectives I, II, III, & VI. 600 people can be served with 2kWh/day/household, however it is noted that serving this load from renewable energy sources requires a large initial capital investment. It was found that the microgrids are most suited to loads with consumption levels between 50 and 150kWh/day and that do not feature essential services. The lower consumption limit is imposed by the fixed capital costs of constructing a microgrid as discussed in 4.3.2. The upper limit is imposed by the cost of extended storage capacity that is needed for large loads on renewable networks. The net present cost (NPC) target of $200,000 was met for all levels of the hydro microgrid but only the low band solar grid meets the target. It can be deduced that, at least for establishing the first source of power in a community, the supply levels should be kept low. For very low consumption (below 50kWh/day) it is recommended the community trial a DC nanogrid as discussed in 5.1. For any other levels a microgrid is recommended due to it's modular expandable structure.

The supply is stable and relatively reliable but the goal of utility grid level experience has not been met. Even within the optimal load levels it was found that essential services could not be run continuously as the yearly unmet load was around 5-8%. The storage capacity required to cover this is unrealistically large. Any such load, for example a medical centre, could be powered by the network but would require a back-up generator. Objectives IV and V, which have been met, help with the consolidation of objective III. The control methods chosen for V were; inverter based reversed droop control fed by DC battery reference voltage, maximum power point tracking at the solar PV output, and prime mover speed control at the hydro turbine output. The effects of these strategies was not determined during the project. It is a prediction of the research that they would act to reduce both excess electricity and unmet load while potentially reducing storage requirements and cost within each microgrid.

The storage systems chosen for objective IV were li-ion batteries, lead-acid batteries, and PHES. It was quickly determined that the lead-acid battery was inferior to li-ion for this application. The required li-ion battery bank was found to be very large for solar based microgrids and the PHES system in the hydro grid was found to be overly costly, both in section 4.3.3. It was also found that low band consumers with a hydro turbine can access year-round electricity with no storage at all. This is highly promising for rural communities with low capital as it removes the complexity and cost of energy storage. All microgrids tested achieved a grid parity distance of a few kilometres or less meaning that the vast majority of rural residents will pay less for energy from a renewable microgrid than from the national grid. While the government may be unwilling to extend the grid to low consumption villages, for example, connection to a microgrid is highly advantageous for them as discussed in section 3.1. Microgrid investment may then lead to a faster expansion of the national grid which would benefit all.

Comparison between the solar and hydro based microgrids confirm that, for low and medium bands, hydropower has a much lower NPC and cost of energy (COE) than solar. The hydro turbine also has a much higher capacity factor than the solar panels meaning it provides enhanced economic efficiency which is attractive to investors. The major barriers to hydropower deployment are access and, in this case, yearly rainfall fluctuations. While access to hydropower in Rwanda may be high, the dry summer season reduces output by up to three quarters which can seriously affect the viability of the resource. The solar panels however were very consistent and offer a flexible low maintenance energy solution that can be used by any rural community in Sub-Saharan Africa. The future cost trends presented in 3.3.1 & 3.4.1 show that, for solar modules and batteries, price is decreasing rapidly. As these microgrids are built with a projected lifetime of 30 years it may be that a future cost analysis of technologies could alter the results from the HOMER simulations. The expectation is a reduction in costs for the region along all timeframes, a full future cost trend analysis is recommended for future research in 5.1.

The project generally followed the timeplan set out in the proposal although the research stage did take longer than originally anticipated. The majority of the original aims and objectives were achieved although some clear questions remain. The main shortcoming of the project is the lack of power control analysis present in HOMER pro 3.7 which was used for simulations. Other topical research papers ([2], [54], [55], & [56]) are similarly unable to account for the effects of control methods. While this paper may show that a microgrid can compete with a national grid for price it does not explain how to fund the initial capital. Much more progress is needed in political and economic terms before widespread microgrid construction across the continent. In the meantime it is vital that engineers continue research to bring down the costs and complexity associated with distributed microgrids. Some suggested research areas are discussed in 5.1.

5.1 Future research areas

As mentioned in this paper the study of distributed generation and microgrids is still very much focussed on western climates and infrastructure. While much progress has been made, more research needs to be directed to microgrids in general in order to ease our grid networks and bring electricity to rural populations.

Control optimization

One area for future research is to develop Simulink control strategies for the microgrids presented and in line with the overall goals of simplicity and economic efficiency in a Sub-Saharan environment. This can be achieved through custom control development in Matlab Simulink. The cost benefit analysis of different control methods should be presented and their effects discussed. Additionally the effects of load control and smart meters can be discussed. Load control is discounted from this project but load shaving can offer large economic savings so any future research should take it into account.

Anchor loading

Anchor loading is a method to increase power quality and capacity factor, particularly for the solar microgrid. An anchor load has a continuous electrical need but it is a deferrable load so can be powered purely by excess energy. An example of a practical anchor load is an irrigation system that is powered only in the daytime by excess solar power. For a hydro microgrid street lighting could be used over night when the load requirement is otherwise low. Anchor loading offers huge potential for increased efficiency while providing essential services. Precise analysis of electrical effects and costs is required.

Nanogrid optimization

A second unexplored area is that of the low load consumer who, for these simulations, is priced out of a microgrid by the high fixed capital costs of installation. Reducing fixed capital costs for the construction of microgrids is a high priority but for very low load consumers nanogrids may offer a better solution. Solar Home Systems (SHS) are examples of nano grids that supply a single house. The nano grid can be expanded and companies such as MeshPower (meshpower.co.uk) are developing DC nanogrids with low fixed capital cost in mind. DC nanogrids hold huge potential for wide scale electrification across Africa due to the very low capital costs. More research is needed on DC nano and microgrids, their advantages and shortcomings, and the barriers to large scale deployment.

Microgrid global markets
For this project AIMS Power was used as the main supplier as it services the region of Sub-Saharan Africa. Future studies may focus on the global marketplace for microgrid components, trading routes, and internal production costs. Comparison of costs related to importing Chinese products and importing Egyptian products for example would provide valuable insight into cost reducing policies.

Future cost trend analysis
A study of the effects of falling costs in solar PV, battery, and inverter markets on microgrid deployment in Sub-Saharan Africa would offer valuable information for regional planning. A future cost analysis could be presented as a natural continuation from this project, using similar methods and tools.

Alternative storage technologies
The storage technologies compared in this paper are some of the most common but many more viable options exist that could be assessed for viability in Sub-Saharan Africa. Some examples are flow batteries, compressed air energy storage (CAES), flywheels, and community battery energy storage. The perfect energy storage system is yet to be found but a deeper analysis of some of these and other new storage technologies would provide insight into the choices available for Rwanda and similar countries.

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Appendix

I Power theory fundamentals

This is a brief introduction to power theory and covers the bare minimum needed to appreciate the concepts discussed in this paper.

The simplest power grid is one with resistive qualities. Resistors act to dissipate power by the following relation:

$$P = VI = \frac{V^2}{R} = I^2 R \quad (1)$$

On a transmission line the power equation relates to the amount of power lost. To reduce power loss it is preferable to decrease current by an increase in voltage. In a resistive circuit the current and voltage are always *in phase* so the power P is always positive. This quality makes resistance a *real* entity, the cousin of resistance R is reactance X which has qualities that make it an *imaginary* entity. A combination of resistance and reactance makes the *complex* entity impedance Z;

$$Z = R + jX \quad (2)$$

Reactance is related to both inductance L and capacitance C by the system frequency f, meaning the reactance of a system is highly dependent on the frequency of the network:

$$X_L = 2\pi f L \quad (3)$$
$$X_C = \frac{-1}{2\pi f C} \quad (4)$$

Here it can be seen that inductors generate reactance while capacitors absorb it. Including reactance in Ohm's law gives:

$$V = I(R + j\omega L - \frac{j}{\omega C}) \quad (5)$$

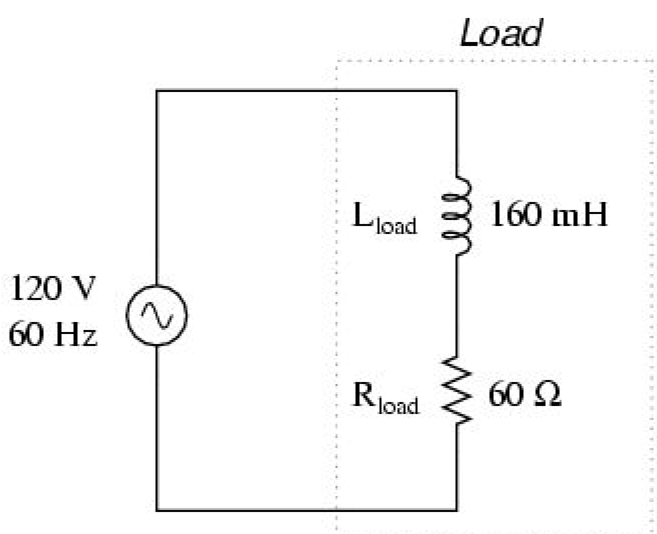

Figure A1: LC load circuit[57]

Example:

The circuit in figure A1 displays an AC voltage source in series with a complex load consisting of resistance and inductance.

$$X_L = 2\pi f L = 60.319\Omega$$
$$Z = R + jX = 60 + j60.319\Omega$$

As with all complex numbers the impedance may be expressed in polar form:

$$Z = 85.078\Omega \angle 45.192^o$$

The angle here is the phase angle of the circuit, phase angle can be seen as a measure of the proportion of reactance to resistance. A phase angle of 0^o indicates a purely resistive circuit or one in which capacitive and inductive reactance cancels out.

Returning to the power equation (P=VI) it should be noted that with a complex load the power itself becomes complex. Power is now composed of active power P and reactive power Q, the total power is called apparent power S.

$$S_1 = V_1 I_1 = P_1 + jQ_1 \quad (6)$$

Active power or true power is that which is dissipated by resistors, this is power that does real work in the system. Reactive power does no real work, generally the aim in power systems is to reduce reactive power at the load, mostly by balancing the production and absorption using inductors and capacitors as mentioned previously. This is part of the role of system controllers that increase and decrease active and reactive power to 'balance' the system.

For power transfer over a transmission line, input voltage V_1 is related to load voltage V_2 by:

$$V_1 = V_2 + ZI_1 \quad (7)$$

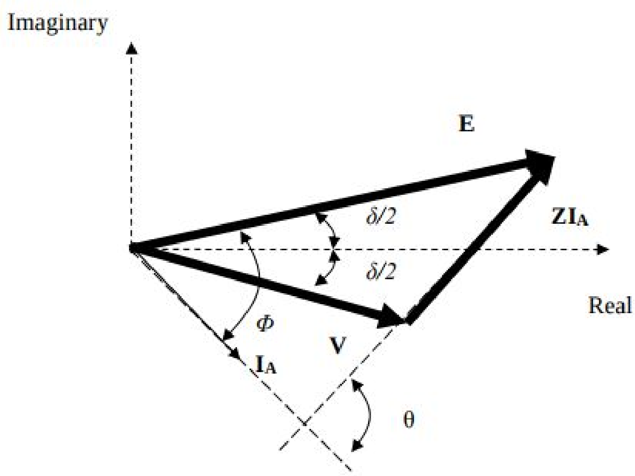

Figure A2: Phasor diagram of transmission line

Where Z is the total impedance, the characteristics of the impedance are described by:

$$\theta = tan^{-1}(\frac{X_L - X_C}{R}) \quad (8)$$

The phase angle between supply and load voltages is the load angle δ.

All relationships within a complex power system can be visualised by a phasor diagram such as figure A2 (E is supply V_1 & V is load V_2).

The full equations for active and reactive power flowing into any transfer line can be found by calculating the apparent power (equation 6) for the current of (7):

$$S_1 = V_1 I_1 = V_1(\frac{V_1 - V_2}{Z}) \quad (9)$$

Expressed in polar form as:

$$S_1 = V_1 e^{j\delta/2}(\frac{V_1 e^{-j\delta/2} - V_2 e^{j\delta/2}}{Ze^{-j\theta}}) = \frac{|V_1|}{Ze^{-j\theta}} - \frac{V_1 V_2 e^{j\delta}}{Ze^{-j\theta}} \quad (10)$$

Separated into real and imaginary components gives:

$$P = \frac{V_1^2}{Z}cos(\theta) - \frac{V_1 V_2}{Z}cos(\theta + \delta) \quad (11)$$
$$Q = \frac{V_1^2}{Z}sin(\theta) - \frac{V_1 V_2}{Z}sin(\theta + \delta) \quad (12)$$

These are the fundamental equations for a system containing both resistance and reactance. Active power is measured in Watts which is defined as the rate of energy consumption so 1 Watt is equal to 1 Joule per second. Energy consumed in a system is not usually measured in Joules but in Kilowatt hours. 1 Kilowatt hour of energy is equal to 3.6 megajoules or 1 kilowatt of constant power consumed over one hour.

II HOMER

Hybrid Optimization of Multiple Energy Resources (HOMER) is a simulation tool designed by the US National Renewable Energy Laboratory (NREL). It was originally designed for use in off-grid villages in developing countries making it an obvious selection for this project. As the name suggests it is specifically adapted to optimizing systems that have a hybrid of resources and paper reviews such as [58] show that HOMER is a leader in its field in terms of accuracy, relevance and ease of use. Both HOMER Legacy and HOMER Pro 3.7 were used during this project. Once all input parameters are defined by the user, the principle tasks that HOMER performs are:

- Simulation - Modelling the performance of the system for each hour in a year to determine the technical feasibility and the life cycle cost of the given system configuration and operating strategy.
- Optimization - Simulation of a number of different system configurations aiming to find one that satisfies the technical constraints at the lowest life cycle cost.
- Sensitivity Analysis - Consideration of the effects of user defined input variables and uncertainty.

Other project inputs

Each project requires general inputs about the economic condition in which it will perform. Unless stated these will be the same for both microgrids.

Nominal discount & Inflation rates:

The nominal discount rate and the expected inflation rate are related to the national interest rate by the following equation:

$$i = \frac{i' - f}{1 + f}$$

Where i=interest, i'=nominal discount & f=expected inflation.

Rwanda has an interest rate of 6.25% and inflation of around 12%, from the equation it can be shown that nominal discount rate is 19%. High inflation and interest rates mean investment is costly and the net present cost (NPC) of a project may be much lower than the future cash flows suggest.

Project lifetime:

Both the solar panels and the hydro turbine have a lifetime of 30 years, the battery and converter both have lifetimes of 15 years so project lifetimes of 30 years were chosen. This will require exactly one battery and converter replacement each.

System fixed costs:

The system fixed costs are costs that are incurred regardless of the specific topology of the grid. This includes wiring, transportation, civil works costs, and operation and management. For the solar grid we will estimate a fixed capital cost of $30,000 and a fixed O&M cost of $200/year for broken cables and general repair. This represents around 6-15% of total solar costs depending on load band. The hydro grid is estimated at a fixed capital cost of $50,000 with a fixed O&M cost of $200/year. This represents around 25-30% of total hydro costs depending on load band.

Minimum annual capacity shortage:
This value is a percentage of total capacity that may be left unserved. Assuming the community does not house a medical centre or other essential services, this is set to 10%.

Grid extension:
The cost of the microgrid can be compared to that of extension of the national grid line to the village. The cost of extending a 33kV distribution line is $23,000/km[59], once grid connected the cost of electricity is dependent on the level of consumption. For low consumers of 0-15kWh/month the charge is 89FRw/kWh equal to $0.11/kWh, consumers of 15-50kWh/month the charge is 182FRw/kWh which is $0.22/kWh, for consumers over 50kWh/month the charge increases only slightly. Assuming an incremental tariff policy the 15-50kWh/month consumers will pay the lower rate for their first 15kWh and higher rate over 15kWh. HOMER does not allow for incremental tariff rates so will inflate grid rates for the higher level consumers. This will be an additional consideration when discussing grid extension.

III Results

The results presented here are the key figures, first in financial terms followed by electrical, for the grid chosen to be most optimal for each generation type and load. Full hourly results are submitted along with this document as data files within the file HOMER_Results.zip.

Solar Microgrid

Low band:

Component	**Capacity**	**Quantity**	**Total NPC ($)**	**Annualised cost ($/year)**
Solar PV	77.9kW	312	89,339.57	6,664.99
Li-ion battery	134.8kWh	132	74,066.69	5,525.59
Inverter	15.7kW	1	5,858.20	437.04

Other costs: $32,680.87
Total NPC: $201,945.33
Total annualised: $15,065.69
Annual cost per person: $25.11

Parameter	**Value (kWh/year)**

PV output	98,934
Load	58,721
Excess	31,463.8 (31.8%)
Unmet load	5,153.8 (8.1%)

Medium band:

Component	**Capacity**	**Quantity**	**Total NPC ($)**	**Annualised cost ($/year)**
Solar PV	109kW	438	125,410.41	9,355.97
Li-ion battery	208.32kWh	204	114,466.70	8,539.54
Inverter	27.3kW	1	10,573.12	788.78

Other costs: $32,680.87
Total NPC: $283,131.10
Total annualised: $21,122.38
Annual cost per person: $35.20

Parameter	**Value (kWh/year)**
PV output	125,567
Load	83,730
Excess	29,111.7 (23.2%)
Unmet load	7,520.0 (8.2%)

High band:

Component	**Capacity**	**Quantity**	**Total NPC ($)**	**Annualised cost ($/year)**
Solar PV	178.93kW	716	205,168.76	15,306.17
Li-ion battery	361.5kWh	354	198,633.39	14,818.61
Inverter	40kW	1	15,575.26	1,161.96

Other costs: $32,680.87
Total NPC: $452,058.28
Total annualised: $33,724.83
Annualised per person: $56.21

Parameter	**Value (kWh/year)**

PV output	203,432
Load	134,504
Excess	48,095.2 (23.6%)
Unmet load	11,495.7 (7.9%)

Hydropower Microgrid

Low band:

Component	**Capacity**	**Quantity**	**Total NPC ($)**	**Annualised cost ($/year)**
Hydropower turbine	25kW	1	115,765.92	8,636.47
Inverter	11kW	1	4,649.07	346.83

Other costs: $32,680.87

Total NPC: $152,631.67

Total annualised: $11,421.39

Annual cost per person: $19.04

Parameter	**Value (kWh/year)**
Hydro output	174,283
Load	60,088
Excess	107,518.7 (61.7%)
Unmet load	3,787.2 (5.9%)

Medium band:

Component	**Capacity**	**Quantity**	**Total NPC ($)**	**Annualised cost ($/year)**
Hydropower turbine	25kW	1	115,765.92	8,636.47
Inverter	19.1kW	1	7,341.61	432.43
Li-ion battery	30.64kWh	30	16,833.34	1,255.81

Other costs: $32,680.87

Total NPC: $172,621.74

Total annualised: $12,878.07

Annual cost per person: $21.46

Parameter	Value (kWh/year)
Hydro output	174,283
Load	84,490
Excess	80,150.3 (46%)
Unmet load	6,759.9 (7.4%)

High band:

Component	Capacity	Quantity	Total NPC ($)	Annualised cost ($/year)
Hydropower turbine	25kW	1	115,765.92	8,636.47
Inverter	47.8kW	1	18,635.96	1,390.30
PHES	7,370.64kWh	1	1,414,862.24	105,552.74

Other costs: $32,680.87
Total NPC: $1,581,944.99
Total annualised: $118,017.58
Annualised per person: $196.70

Parameter	Value (kWh/year)
Hydro output	174,283
Load	133,511
Excess	20,679.5 (11.9%)
Unmet load	12,488.8 (8.6%)

IV List of Abbreviations

CAES - Compressed Air Energy Storage
CHP - Combined Heat and Power
COE - Cost of Energy
DS - Distributed Storage
GDP - Gross Domestic Product
LC - Load Controller
MC - Microsource Controller
MGCC - Microgrid Central Controller
MPPT - Maximum Power Point Tracking
NPC - Net Present Cost
NREL - National Renewable Energy Laboratory
O&M - Operation and Management
PCC - Point of Common Coupling
PHES - Pumped Hydro Energy Storage
PSP - Private Sector Participation
PV - Photovoltaic
PWM - Pulse Width Modulation
SHS - Solar Home System