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Consideration for a Sustainable Hybrid Electric Power Mini-grid: Case Study for Wanale Village in Uganda.

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DECLARATION

I, Raymond Kimera, know the meaning of plagiarism and declare that all the work in the dissertation, save for that which is properly acknowledged, is my own.

Signed____

Date ____

ABSTRACT

The reliance on diesel generators for off-grid electrification has become unsustainable, mainly due to the uncertainty surrounding the price and availability of fossil fuels. The integration of renewable energy technologies into power networks has provided a backbone for the electrification of locations that were previously constrained by their distance from the national electricity grid.

The intermittent nature of renewable resources, however, poses a challenge as energy generation does not always coincide with usage. This necessitates additional capital costs in over-sizing systems to ensure dependable supply, and thus the need for energy storage. Additionally, in cases of extended periods of low resource supply, such as over cast days, there will be shortages even when energy storage is available. Consequently, immense losses may be incurred particularly in cases of uninterruptible services such as the storage of vaccines and perishable goods like fish.

Through a combination of renewable energy technologies and conventional diesel generation, a hybrid mini-grid system is able to achieve synergy in operation, providing quality, reliable and affordable electricity services. This technology is capable of achieving rapid rural electrification, especially in sub-Saharan Africa where the biggest portion of the population resides in remote villages.

In this study, a hybrid mini-grid system is designed to supply electricity to a rural village in Uganda. Renewable energy resources are identified, an estimation of the projected village short-term electricity demand is simulated, and using HOMER software, a hybrid mini-grid system is designed, components sized, and the system optimized in terms of cost, and efficient and reliable operation to meet the village demand. Further recommendations are then made on ways to improve the affordability of rural energy services, and alternative operational configurations and scenarios are presented.

Through the simulation of different configuration scenarios of the supply system, based on the load and available resources, the most effective hybrid mini-grid system design is established to combine hydro and solar PV, with battery energy storage and diesel generator included as backup supply. This system is demonstrated to be more reliable and efficient in operation, and the most cost-effective for the required level of service. The role of energy storage in system operation is also demonstrated to offer additional operational advantages in-terms of efficiency, reliability and cost savings.

Though the system is simulated to offer technical superiority in operation, the energy cost is determined to be higher than what rural consumers would be able to afford. Thus scenarios and recommendations are presented that could enable affordability in rural mini-grid system operation and design.

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Thank you mummy

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Angela, you are a special person.

It’s been a pleasure Lesego

My Family…………..see you all in a bit.

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Acronyms

Notation	**Definition**
AMI	Automated Metering Infrastructure
CDM	Clean Development Mechanism
COE	Cost of Energy
GETFiT	Global Energy Transfer Feed-in-Tariff
IPCC	International Panel on Climate Change
LOEE	Loss of Energy Expectation
LOLE	Loss of Load Expectation
LCOE	Levelized Cost of Energy
MEMD	Ministry of Energy and Mineral Development
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
O & M	Operation and Maintenance
PEMFC	Proton-Exchange Membrane Fuel Cell
PV	Photovoltaic
REFiT	Renewable Energy Feed-in-Tariff
RPT	Renewable Energy Premium Tariff
SHS	Solar Home System
SOC	State of Charge
TNPC	Total Net Present Cost

1. INTRODUCTION

1.1 Background

The absence of electricity greatly impacts the lives of many people in Uganda. Like many third-world African countries, Uganda faces the challenge of providing reliable electricity to most of its population. With the share of people connected to the national grid at 9% and mainly in the urban areas, only 3% of the rural population in Uganda has access to electricity. This is despite the fact that 85 % of the population live in rural areas, and mainly engage in subsistence agriculture for food and a livelihood (Okure, 2009). The fact that Uganda is a developing country with a large rural population presents the energy utility and regulators with a number of challenges as depicted by (Ezor, et al., 2009).

- First and foremost, there is insufficient generation capacity to meet the electricity demand in Uganda. Therefore the electricity transmission and distribution utilities tend to concentrate on supplying the areas/consumers nearest to the main power stations, and to reliable customers in urban areas.
- Secondly, the cost of transmitting and distributing electricity to rural areas is high, this coupled with the difficulty of the terrain to most of the rural areas makes grid extension unfavourable to most utilities.
- Furthermore, the lack of generation capacity plays an important role in the decisions for electrification. Given the smaller sizes of rural demand, it often doesn't make sense financially for a company with limited supply to transport and distribute that supply to rural areas, when urban areas with relatively more reliable customers need the electricity.
- Also, in Uganda, the location of rural areas imposes a greater risk to the theft of power equipment and the power itself due to meter looping and illegal connections. This increases revenue losses, making it more difficult to justify rural electrification.
- High electricity tariffs also constrain the affordability of rural consumers, without subsidies or government support, extending energy services to poor consumers

hundreds of kilometers from the nearest power plant, who will struggle to afford the service, is not economical.

Uganda’s electricity consumption is 55% residential, 25% commercial and general, and 20% industrial (Frances, 2002). The rural communities, like in most developing countries are characterized by low population densities and low electric power demand, with the demand for electricity dominated by domestic consumers and small businesses. Domestic electricity needs are mainly for lighting, audiovisual (televisions and radios) and operation of other small appliances e.g. phone charging. Commercial applications are for small business applications such as shop-kiosks, saloons, bars, restaurants, etc. Other sectors which might need electricity in rural areas include local government offices, a health center, education institutions etc. Common appliances such as lights, radios and televisions are found in households as well as public places such as bars for entertainment, news affairs, and education (Lhendup, 2008).

1.2 Problem Statement

Without access to modern energy services many rural communities struggle to obtain the resources necessary to lift them out of a static state. Wanale village in Eastern Uganda faces these same challenges. Many of the members in this community are subsistence farmers. Energy services are provided through local resources such as kerosene for lighting, and fuel wood for cooking.

1.3 Justification

Electrification can act as a catalyst for the social and economic development of this village. For such a community, electrification would allow the members access to modernized health care, modern communication services, and increased availability of light to extend work and engage in income generating activities (Micro Power Group, 2010).

1.4 Hypothesis

A hybrid electric power system can provide a reliable and cost effective solution to the electrification of Wanale village.

1.5 Objectives

The main objectives of this study therefore include:

I. To quantify the available renewable resource potential at Wanale;
II. To simulate the short-term electricity demand forecast at Wanale;
III. Based on the available renewable resources and village demand, a hybrid electric power system will be designed, sized and optimized for affordable and reliable operation to supply electricity to the Wanale community.

With specific objectives:

I. To investigate options for making rural electrification affordable, and also the role of energy storage in the hybrid electric power system's and operation;
II. To investigate and recommend future technology considerations and advancement in hybrid mini-grid design.

1.6 Methodology

A systematic approach to the design of a hybrid mini-grid system is done in this thesis. A location is identified at Wanale village, available renewable resources are established, and load modeling done to determine the projected short-term village demand. Using HOMER software, a mini-grid system is designed to meet the Wanale demand. This system is them optimized for operational reliability and affordable operation.

The members of Wanale village, Eastern Uganda, identified the potential to harness the available hydro resources from river Wanale. A short-term electricity demand forecast is then modeled based on predicted demand of the community members to determine the immediate load. HOMER software was then used to design a hybrid mini-grid system to meet the predicted village demand. It was determined that the hydro supply would be insufficient to meet the projected short-term village demand. Thus the system is also designed to include generation from the available solar resources; and in order to ensure system reliability, a diesel generator and battery energy storage are also included in the system design to provide the necessary backup supply.

HOMER software, developed by the National Renewable Energy Laboratory (NREL) in the USA is a sizing, simulation and optimization tool for renewable energy system design. It is thus used in this study to determine the optimal system for the provision of electricity to Wanale community (NREL, 2005). System analysis with HOMER requires information on the resources, economic constraints, and control methods. Input information will include: village demand (one year of load data), renewable resources, component technical details and costs, constraints, controls, type of dispatch strategy (NREL, 2005). HOMER then calculates the Levelized Cost of Energy based on inputs for the capital cost, replacement cost, operation and maintenance cost, fuel cost, and discount rate, using the formula below.

$$\text{LCOE} = \Sigma_t\,[\text{Costs}_t \times (1+r)^{-t}]\ /\ \Sigma_t[\text{Electricity}_t \times (1+r)^{-t}] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \mathbf{(1)}$$

Where; *t* represents the operation year, and $\text{Electricity}_{t,}$ is electricity generated in year t,

$$\text{Costs} = \Sigma_t\,[(\text{Investment}_t + \text{O\&M}_t + \text{Fuel}_t + \text{Tax}_t + \text{Other}_t)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \mathbf{(2)}$$

r is the discount rate accounting for the time value of money;

And, the investment costs are the initial capital charges for setting up each technology including labour, while the Operation and Maintenance (O&M) costs cover the annual operating costs. These O&M costs include the fixed costs which cover the equipment service, salaries, and the variable costs which include the fuel costs, and these mostly apply to the diesel generator. HOMER will then optimize the system by simulating the various system configurations in search for the one that satisfies the village energy needs at the lowest Life Cycle Cost. It will then display a list of configurations sorted based on their Net Present Cost (NPC), which is then used to compare system design options.

Also included in the simulations is a range of sensitivity variables defined for the fuel cost, HOMER then performs multiple optimizations, to assess the effects of uncertainty or changes in these variables which the designer may not have control over. The software also includes a grid extension module, which is used in this case to make a cost comparison between the stand-alone hybrid power system and the traditional extension of the electrical grid.

HOMER software is then used to simulate various configuration scenarios to predict for the evolution of the mini-grid to include future scenarios such as fuel cells and grid integration.

1.7 Outline of the Thesis

This thesis was prepared with every effort to ensure simplicity towards the reader, with the structure organized as below.

- Chapter 2 presents background literature on the available solutions to off-grid electrification, thus leading up to an introduction to hybrid mini-grid systems. Also, background literature on rural electrification efforts in Uganda is presented.
- Chapter 3 presents the case study, Wanale village, highlighting the village condition and the people's need for electricity services.
- Chapter 4 presents the system design and modeling process. The parameters of the hybrid mini-grid system are established; the system is designed, sized and optimized in HOMER software for reliable operation and affordability. Different operation scenarios are presented leading up to the proposed system design and operation.
- Chapter 5 presents different scenarios for future considerations in the hybrid mini-grid system operation and design.
- Chapter 6 concludes the thesis with a summary of the results, discussion and some recommendations.

2. LITERATURE REVIEW

2.1 Off-grid Electrification

The applicability of renewable energy resources for power generation has provided options for the rural electrification process that were previously constrained for such reasons as (O. Dzune Mipoung, 2009):

- The problem with the dispersal of villages in most developing countries
- Relatively higher electrification cost for villages located hundreds of kilometers from the closest power plants and or utility grids.
- The complications with alternatives to grid extension

Two typical types of off-grid electrification options have thus found application:

2.1.1 Energy Home Systems

These include solar home systems (SHS) and wind home/farm systems. These are small home supply systems usually in the ranges of 10 to 100Wp, but can range up to 500Wp depending on the region. In the systems, the power generation (mainly PV) is installed to match a specific load (a few light-hours, radio or TV-hours). The total energy cost of the system tends to be higher due to the lack of economies of scale. Therefore to keep the systems affordable, components are minimized and capacities are low for the provision of basic electricity services. In most cases, energy home systems are not targeting to promote income generating activities, however in some areas they can indirectly generate income e.g. cottage activities such as women weaving mats. These though, can be useful in eliminating the need for candles, kerosene lamps, and can provide for basic applications such as battery charging; providing higher quality lighting and charging services (Rolland Simon & Guido Glanio, 2011). A diagram of a solar home system is shown in figure 1.

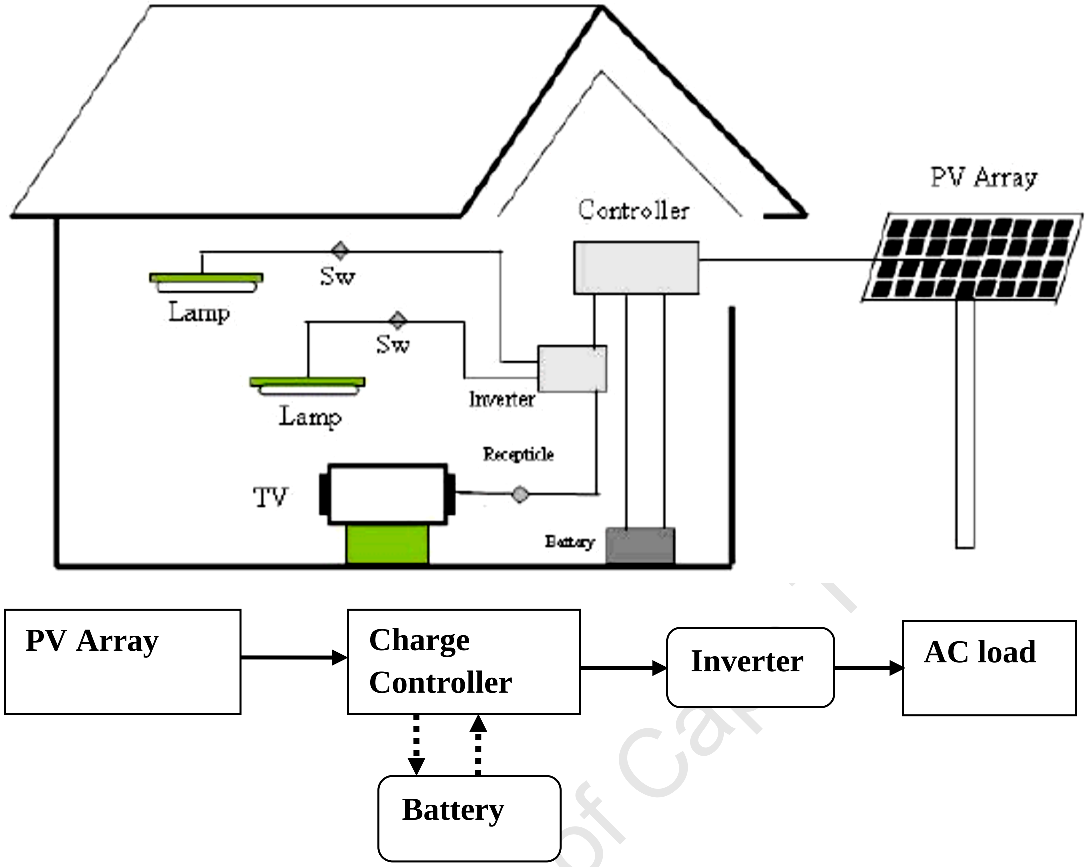


Figure 1: Diagram of a SHS (Source: (Siripatrodom, 2006))

2.1.2 Village-scale mini-grids

Village-scale mini-grids offer an alternative solution to grid extension for rural electrification. These remove the need for long and costly transmission lines, as electricity supply in the form of mini-grids are setup close to the point of need. A schematic representation of such a system is shown in figure 2. Centralized mini-grids can provide capacity for both domestic utilization and also support the growth of local businesses in rural communities. Centralized mini-grids theoretically have the potential to become the most powerful technological approach for accelerated rural electrification (Rolland Simon & Guido Glanio, 2011). And because the distribution systems are similar to the central electricity grid, the option still remains for future upgrade through grid connection.

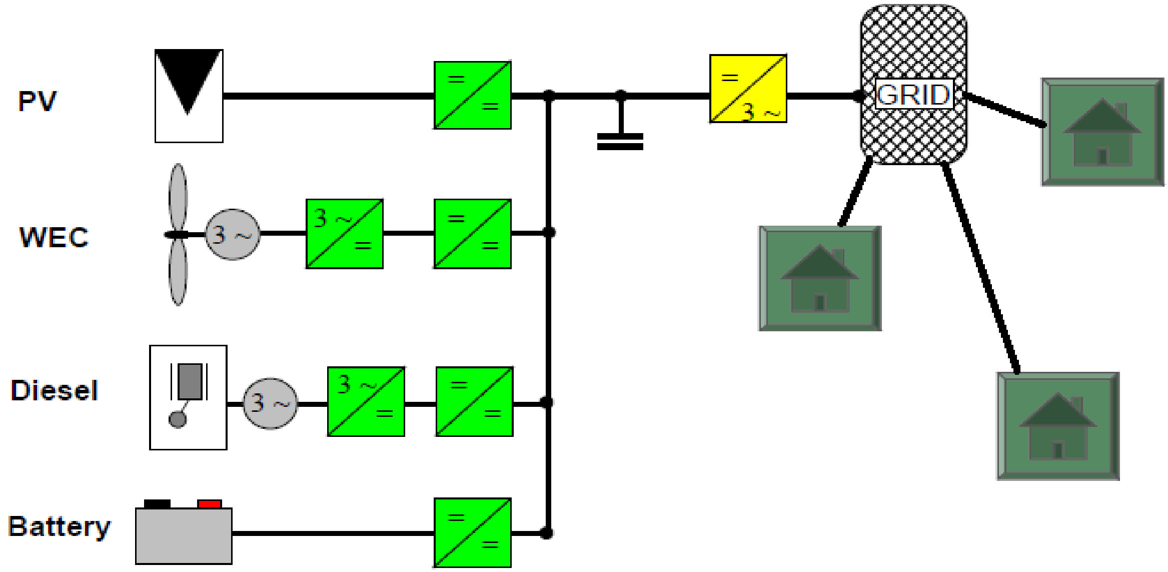


Figure 2: Schematic diagram of a mini-grid structure (source: (Michel, et al., 2010))

2.2 Village-scale Hybrid Mini-grid Systems

The decision on the type of generation source to use is central to mini-grid system design. Initially low capital costs had often favored diesel generators for mini-grid application. However, diesel is an expensive resource, and diesel generation is associated with high life cycle costs due to its high fuel requirements (N.M.Ijumba & C.W.Wekesah , 1996). And given the recent instabilities in the price and availability of fuel, diesel-only mini-grid systems have become unsustainable. Additional disadvantages of diesel mini-grids include;

- Their affiliated air and noise pollution levels are not good for the people's health and the environment
- Also, given the location of many rural areas, the fuel for the system is transported over long and mostly poor road infrastructure, incurring higher transportation costs, and also the risk of theft and accidents.

- And given that rural loads vary greatly during the day and night, diesel generators that can only operate at full capacity are usually operated inefficiently in periods of low demand, thus impacting their operational lifetimes.

Such factors have rendered the current reliance on diesel generator systems unsustainable for village-scale mini-grid application.

Due to the steady increase in global power generation demand, in addition to the conventional power generation sources, a large number of renewable energy sources have been integrated into the power generation system. Because of the issues associated with diesel-only mini-grids, renewable energy technologies have in recent years become a popular choice for application in rural electrification projects. Among the renewable resources, mini-hydro, biomass, wind and solar have been the standout participants for mini-grid applications. Renewable energy resources are free, limitless and available at almost any location (Dali, et al., 2010). But as always, such opportunities come with a number of challenges. Resources such as geothermal, hydro and bio-energy are able to provide stability, reliability, and a certain degree of affordability in their power delivery . However, this is not the case for others such as wind and solar. Implementing these comes with some challenges (Lhendup, 2008):

- First of all, these resources have daily and seasonal variations. This presents a challenge in matching the available resource with the fluctuating demand, adding to the complexity of employing these resources.
- Secondly, renewable energy technologies are characterised by high initial capital costs, resulting in high energy costs for the corresponding generated energy. This provides a challenge of affordability for rural consumers.
- Furthermore, although renewables offer a sustainable energy resource, it is equally important to ensure stability, reliability, affordability and adequacy in the electricity supplied to households, as well as other income generating and social

development faculties. However, for intermittent resources such as wind and solar there is a need for more innovative ways to optimize their utilization.

- It should also be noted that, current cost comparisons between electricity generated from renewable energy technologies and from the equivalent fossil fuel generators, favors the later. This presents a challenge in justifying the alternative to some customers.

Therefore, mini-grids combining both renewable and conventional diesel generation systems have been determined to provide the most competitive technical solution, providing a higher level of energy reliability, at a cheaper cost. These are termed hybrid mini-grid systems. Combining these multiple technologies enables the system to overcome limitations inherent in either (Panapakidis, et al., 2009).

Hybrid mini-grid systems are designed to incorporate renewable energy generation technologies with a conventional diesel generator, thus addressing limitations in terms of fuel flexibility, reliability, emissions reductions, efficiency and economics. The application of this technology can be boundless especially for rural electrification. Hybrid mini-grid systems are capable of providing 24h grid-quality electricity, better efficiencies, and flexibility in planning and operation (Setiawan, et al., 2008). Additional advantages include:

- The maintenance and fuel costs of the generator are signififcantly reduced as the diesel generator only operates when need arises.
- The system also provides opportunity for capacity expansion to cope with increasing future demand.
- The synergy achieved by combining the renewable energy generator and the diesel genset also offers the least-cost supply option.

However, like any technology, hybrid mini-grid systems have a number of challenges that require some attention in order for successful implementation. Decisions regarding the success of the system will not only depend on parameters such as the resources, load and topology, but also other parameters such as the willingness to pay, and the consumption growth in the households. Also, mini-grid life cycle cost are often unknown to a large extent, due to site specific conditions such as village topogoraphy, local conditions affecting the components, and time series data such as weather.

Hence a general recommendation for the optimal mini-grid system design cannot be given, as a number of assumptions are made in the system design. Mini-grids are site specific, require significant preparation which requires time, money and capable consultants to identify and design feasible projects. More importantly, they require institutional support in the form of government policy to support and encourage investors willing to undertake such projects.

2.3 Rural Electrification in Uganda

2.3.1 Uganda's energy policy

There is widespread energy poverty in Uganda, and this is inspite of the abundant hydrological and renewable energy resources. There is therefore urgency in the need to develop these resources and improve energy supply to the people of Uganda. This led to the outline of Uganda's energy policy goal (2002): "*To meet the energy needs of Uganda's population for social and economic development in an environmentally sustainable manner*" (MEMD, 2002:5). Given that energy development and the environment are convoluted, the policy recognized the need to adress both issues. With the foundation of the Energy Policy for Uganda (2002), the Ugandan Government approved a Renewable energy policy vision in 2007 designed to reinforce its commitment to the provission of environmentally sustainable energy access. The outline vision is "*To make modern renewable energy a substantial part of the national energy consumption."* With the overall Renewable Energy Policy goal *"To increase the use of modern renewable energy, from the current 4% to 61% of the total energy consumption by the year 2017"* (MEMD, 2007).

Given the electricity shortage facing Uganda through the lack of capacity and infrastructure, it is within reasonable assumption that electrification of most parts of the country through grid extension in the near future is still a far cry. It is thus, within this context that Government is promoting the distributed (off-grid) electricity supply model for remote areas. Through the deployment of the readily available renewable resources such as small hydro, solar, or biomass, the required electricity needs of these areas can be met. Also with the focus on decentralized electrifiaction, the objective of equitable regional distribution access to electricity can better be achieved than through the persuit of grid electrification (MEMD, 2007).

The Ugandan Government's continued strive for rural electrification has led to the implementation of a number of mini-grid systems over the last decade. Mostly based on diesel generators, the majority of these systems have gone on to fail due to high fuel costs, consumer dissatisfaction, and mismanagement (Ezor, et al., 2009). Section 2.3.2 through to 2.3.4 reviews some of the documented cases of mini-grid operation in Uganda.

2.3.2 Magale village, diesel genset mini-grid

Magale, a small village of about 6,000 people in Eastern Uganda, is located 30km from the national electricity grid. The electrification of Magale was mainly the initiative of a Catholic Mission which donated the generator, with installed equipment and accessories donated through individual donations rather than institutions. The mini-grid system consisted of a diesel powered generator (37.5kVA) to supply electricity to the small hospital whose services grew to include Community Based Health Care among others. Thence a diesel generator was installed in 1999 to provide for better lighting for night time operations, due to the increase in the number of patients. Because the generator capacity initially exceeded the needs of the hospital, a decision was made to sell the excess electricity to the community, and thus 61 households were then electrified in 1999. However, this situation became unsustainable when problems arose from members using heavy electronics which overloaded the system. Subsequently, the over capacity put pressure on the generator, raising the fuel consumption from the initial 23litres, to

25litres for 3hours of daily operation (7pm to 10pm). The electricity tariffs were then increased, but consumers refused to pay, forcing the hospital to halt the electricity sales. Consequently, by the ninth month of operation there were only 36 consumers connected to the mini-grid, while 20 were disconnected (konserve, 2000).

Magale hospital has since then downsized its diesel genset to 3kVA to supply the hospital, and installed a 325Wp solar PV system.

2.3.3 Kalangala mini-grid

Kalangala is the main district of the Ssese islands in Lake Victoria. A government sponsored 250KVA thermal mini-grid was setup in Kalangala district in 2007 for the provision of electricity services to the community. The grid would initially connect a limited number of government buildings, commercial and residential areas in Kalangala town, with more connections expected to be added in time. Mini-grid system operation begun in August (2007), and continued successfully until January (2008) when generation and distribution ceased due to serious flaws in the project. System operation met huddles when consumer capacity was not meeting the generation capacity of the plant. After five months of operation, the plant was providing power to only 20% of the available consumer base, while the operators needed an estimated consumer base of 50% to break even financially, this cost them operational loses of about 5million Uganda shillings per month. High fuel costs were also burdensome in the absence of government subsidies; moreover given Kalangala’s location petroleum products were even more expensive than on the mainland. The limitations by fuel cost and availability were so severe that towards the end of the project’s lifetime power could only be made available to consumers for only a few hours in the evening. This was neither enough to entice new customers nor appease the old.

Among others, the issues that faced the Kalangala mini-grid system are mainly highlighted in the inefficiencies in system planning. Not enough research was conducted to determine consumer capacity and a feasible pan of distribution prior to implementation of the project. First and foremost, the system was oversized. Instead of assuming a projection in the demand at the point of installation, it may have been more responsible to start with a smaller generation capacity and expand the project when consumer capacity increased. This system has since then been replaced by a small generator suitable for a smaller consumer base in Kalangala town (Ezor, et al., 2009).

2.3.4 AC hybrid mini-grid system in Bulyansungwe, Uganda

An AC mini-grid system was installed to power a rural boarding secondary school in the village of Bulyansungwe, Uganda. With no utility lines within several miles, a mini-grid system was the only option for the electrification of this school. This project was an initiative of the German organization, "*Together: Assistance for Uganda"*, which provided funding for its construction and operation. The only previous source of electricity at the school was a small gasoline powered generator which was used on special occasions. It was piloted by Dana Brandt, a graduate student in renewable energy, who was responsible for the design and installation of a PV and engine-generator hybrid system. The installation consisted of a 3.6 kW PV array with a 21.6 kWh battery bank for energy storage, and a 3.5 kW manual start gasoline-generator. The system was designed to supply both electricity and clean water to the school complex.

The system is fully operational, primarily used for lighting, but also used for kitchen appliances such as a blender and mixer, and also a stereo. Bulyansungwe's social center was left un-electrified; however, plans were in place to establish a health center and a basic hospital. Though this would require the erection of more PV panels to facilitate the electrification of these additional units (Brandt, 2005).

2.4 Tariff Setting in Rural Electrification Projects

The determination of the tariff is a central question for the sustainability of an electrification project. A basic rule generally accepted in electrification planning is that, a tariff should at least cover the running costs (O&M) to ensure the ongoing operation of a system throughout its lifetime. It is also widely accepted that rural electrification programs are not the type of projects that will attract private investors looking for somewhere to maximize profits, and only a few have managed a profitable business model.

For the sake of project sustainability, two main types of tariffs have thus been discussed by (Rolland Simon & Guido Glanio, 2011):

1. **Break-even tariffs:** These are designed to ensure just enough revenues to cover system operating, maintenance, and replacement costs. These form the energy price simulated in HOMER. They are more easily affordable to most customers, especially if a subsidy is used to cover the system capital, and customer connection costs (this type of tariff is especially relevant for community-owned systems).

2. **Financially viable tariffs:** These are designed to cover all the system costs, and also allow for sufficient return on investment to attract private sector investors. Private sector involvement may indeed result in higher tariffs, or in higher subsidies to keep tariffs affordable, but also in more efficient operation.

Therefore decision making on tariff structures must keep a balance between ensuring commercial viability (sustainability), and meeting rural consumers' ability and willingness to pay (affordability). Thus rural tariffs must be flexible and tailor made to balance the needs of the utility and the customers.

2.5 Making Rural Electrification Affordable for Rural Consumers

Rural consumers though willing to pay for modern energy services, their ability to afford them is usually limited due to the shortage of resources. And although it is highly recognized that rural electrification is not viable financially, the benefits to rural electrification are vast, and can include among others (Pradeep. K. Katti, 2005):

- Access to better light, increasing working hours to late evening hours and early morning hours, thus increasing village productivity;

- The people get exposed to modern communication (TVs and radios) means through the access to national and global events thus bringing the population in to national mainstream;
- Availability of modern electric energy services motivate the setting up of health centers in rural areas, thus improve health services in the community.

Governments therefore recognize that these schemes can be economically and socially beneficial to rural communities. Thence, the installation of mini-grid systems for isolated rural communities always involves some form of government or donor intervention, to either front the initial capital investment, as a form of fuel levy (in the case of generator run mini-grids), or to subsidize the energy cost (Moner-Girona, 2008).

A number of support mechanisms in the form of funding have been discussed by many authors for the support of renewable energy technologies for rural electrification. Some of these are previewed below.

2.5.1 The Renewable energy Premium Tariff (RPT)

The RPT is a variation of the Renewable Energy Feed-in-Tariff (REFiT). The REFiT has been a successful mechanism in increasing the deployment of renewable energy technologies in grid-connected systems. The RPT is a locally adapted variation of the REFiT scheme, and is a financial scheme designed to help offset the high capital costs associated with most renewable energy projects. This is achieved through paying for the renewable electricity generated, thus encouraging the production of electricity using renewable technology based mini-grids in developing countries. Different possible structures are discussed for the implementation of RPTs in village-grid electrification projects by (Moner-Girona, 2008). The RPT's aim being to achieve different economic purposes, such as affordability for local users, to achieve a return of investment, and to generate earnings for energy service companies countries (Moner-Girona, 2008).

Uganda is among the few countries in Africa exploring the option of encouraging renewable energy deployment through feed-in tariffs. The nation's 2007 Renewable

Energy Policy established a mandate for feed-in tariffs, with the first phase of the Renewable Energy Feed-in-Tariff (REFiT) program running from 2007 to 2009 (MEMD, 2007). This was then reviewed in 2010 due to limited uptake by project developers, and a new tariff was developed based on updated levelized cost of production figures (ERA, 2010). Uganda's REFiT programme offers tariffs on small-scale renewable systems for a whole host of technologies, including geothermal and bagasse, hydro, wind, solar PV. These include a $0.362/kWh solar PV for projects with cumulative capacity not less than 2MW, while for hydro, the $0.109/kW only applies to projects with capacity not less than 500kW. This REFiT is designed for projects with future potential to contribute to the national grid electricity supply (ERA, 2010). The recommendation is for a variation of this scheme to be applicable for those rural areas with limited chance of grid connectivity, whose demand can be met by smaller distributed power systems (mini-grids).

2.5.2 The Global Energy Transfer Feed-in-Tariff (GET-FiT) program

The GET-FiT program is a concept designed to support the development of renewable energy projects, and enable access to clean and reliable energy in the developing world. This is achieved through the creation of international public-private partnerships, such that in this set-up, international AAA-rated donors such as national governments, development banks, and international climate-related funds, contribute premium payments for renewable energy projects in partnership with developing country governments. These payments would be structured in a way so as to support renewable energy technologies' progress towards grid parity, and also to allow developing countries to benefit from the gained experience with renewable resources and technologies prior to break-even scenarios, and by adjusting incentive rates to reflect lower prices over time. This scheme de-risks investors and can establish fair and sufficient returns, as it provides private investors with transparency, longevity and project certainty. The governments of the developing countries and the utilities administer the process, and guarantee to pay the generators at a rate based on the avoided cost of fossil fuel generation. This in the long run, is designed to encourage private investors to deploy capital in renewable energy projects (Fulton, 2010). Fulton (2010) gives a detailed description of the GET-FiT programme and its applicability on a bilateral, regional or global basis.

This scheme fits under the Ugandan government's policy objectives to encourage international partnerships in promoting renewable energy technologies.

2.5.3 Renewable Energy Tradable Certificates

In order to reduce greenhouse gases and mitigate the effects of climate change, countries around the world are encouraging companies to cut down their carbon emissions. The concept of carbon trading involves the transfer of credits, through a direct correlation between carbon emissions and revenue. A carbon credit is equivalent to one metric tonne of carbon-dioxide emitted/ averted. Under the Clean Development Mechanism (CDM), rich countries put limits or caps on the amount of carbon emission by their companies. Such that the companies that need to increase their emissions have to buy credits from those who pollute less, or from green (renewable energy) technology projects from other countries (Daryapurkar, 2008). This scheme allows developed countries to purchase carbon offsets from CDM projects in developing countries.

Under this umbrella, small-scale renewable energy systems for remote area power supply, that rely on solar photovoltaic, wind turbine, small hydro, and biomass technologies among others for their renewable energy input are eligible for creating Renewable Energy Certificates, and consequently give rise to an instrument that may then be traded on a market. With developing countries offering the cheapest option for implementing carbon reduction projects, carbon trading offers a method of transferring wealth, and encouraging sustainable development (Pryor, et al., 2001).

With the Ugandan government pushing for a 61% rural electrification rate by 2017, distributed generation in the form of renewable energy mini-grids offers an opportunity for the country to partner with rich developed countries to create Certified Emissions

Reduction certificates through the Kyoto protocol’s Clean Development Mechanism, which can the be traded.

The criteria for projects eligibility under the CDM include:

- First of all, projects must assist Non-Annex I Parties (developing countries) in achieving sustainable development (Das, et al., 2010). This applies in the context of Uganda, where through renewable energy mini-grids; rural electrification can offer sustainable energy services and thus opportunity for social and economic development to a number of communities around the country.
- Also, projects must result in real, measurable and long-term benefits related to the mitigation of climate change (Myung-Kyoon Lee, 2004). Through modern energy services, traditional energy sources for lighting such as kerosene lamps and candles can be displaced, resulting in lower pollution levels, and also health benefits for the people from the reduced fumes.
- Furthermore, projects must result in reductions in emissions that are additional to any that would occur in the absence of the certified project activity (Myung-Kyoon Lee, 2004). These would include resulting emissions from extending a fossil fueled electricity grid, or a diesel based mini-grid.

3. CASE STUDY: WANALE VILLAGE

Wanale village is located in Mbale district, Eastern Uganda at the coordinates 1.02N, 34.19E (iTouchMap.com, 2011), as shown in figure 3. Uganda is situated in East Africa, with its capital city Kampala district in central part of Uganda. Mbale district lies approximately 245km by road, northeast of Kampala. Wanale trading centre lies 15km east of Mbale town on the southern foothills of Mount Elgon. Traveling from Mbale town takes about 45minutes along murram road to Wanale village.

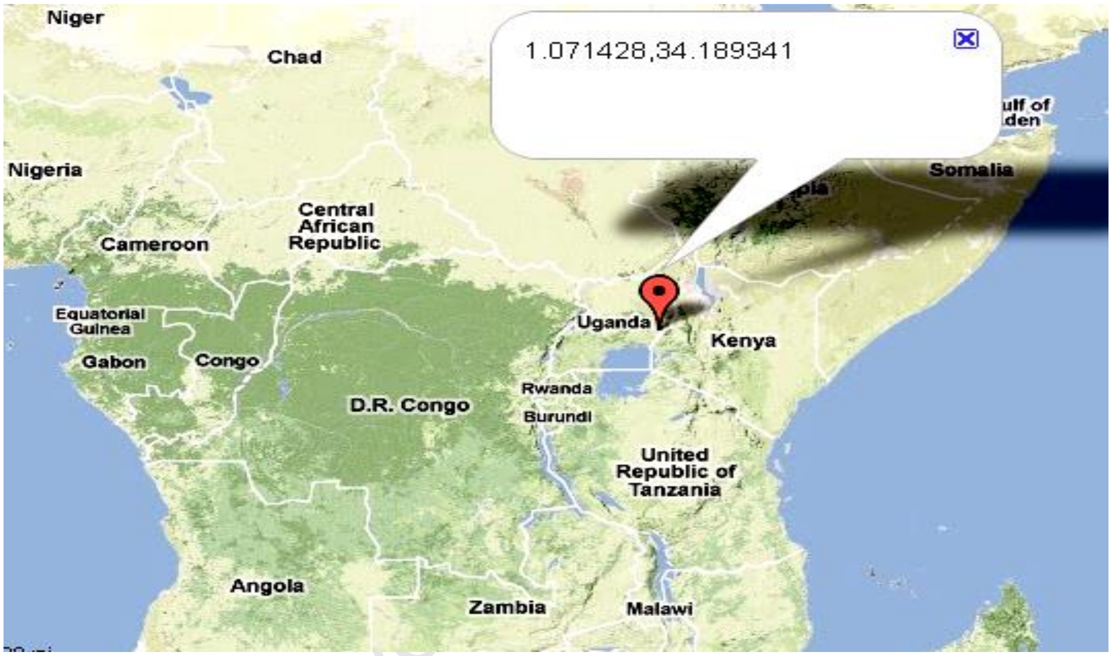


Figure 3: Location of Wanale village, Mbale district, Eastern Uganda

The equator passes through the country, just south of the capital Kampala. This proximity to the equator makes the daylight variations non-existent, with the sun-rise around six in the morning, and falling by seven in the evening. This makes Uganda's average temperature at 25-26° all year round (Frances, 2002).

Wanale village consists of approximately 80 households, of which are mostly residential dwellings. There is also a trading centre, with commercial activity in the form of small shops and markets, restaurants, bars, video show centres, charging stations, and a dispensary among others. Like most rural villages in Uganda, the members of Wanale are subsistence farmers who rely on their farm produce for food and a source of income. Some of the crops they grow include: coffee, maize, bananas, fruits, onions, tomatoes and carrots. Their basic energy consumptions are based on traditional fuel wood and charcoal for cooking, candles and kerosene lamps for lighting, and batteries for their small radios.

Electricity can provide for some of these rural energy needs, substituting for some of the traditional energy sources such as those used for lighting, while facilitating modern communication (television sets and radios), basic appliances such as charging, and other uses such as refrigeration. The nearest utility grid access point, an11kv distribution line closest to this village is 7km away (Micro Power Group, 2010). For a community such as this, a properly designed and sized hybrid mini-grid system can be the most feasible electrification solution to the community's energy needs.

Off-grid electrification is site specific. In the design considerations, the location, available resources, and village demand profile play a significant role in the decision making process. Time is also a major factor as conditions change; the demand grows, and grid extension can become a feasible option in the near future. All these factors need to be considered in the preliminary research. Also, the probability of a successful project will depend on the community's participation; the early assessment phase must integrate an analysis of the local conditions and the rural community's needs. Community involvement and support must be maximized in the design considerations, as the involvement of the local personnel reduces the chances of project failure and any negative image of renewables in the region. Service providers and stake holders need the knowledge and tools to determine the least cost option for a given level of service in a specific period (Rolland Simon & Guido Glanio, 2011).

Through software modeling a generalization of a generation system can be manipulated to better understand the technical behavior of the system under different conditions. Software models act as a desk-top prefeasibility study before the implementation of the actual system.

4. DESIGNING A HYBRID MINI-GRID SYSTEM FOR WANALE VILLAGE

When designing a decentralized rural electrification system, some of the most important aspects to consider include the resource availability and the expected demand. The available resources must be enough to meet the anticipated demand.

4.1 The Resource Availability

The members of Wanale recognized the potential for generating hydro-electric power on river Wanale. A feasibility study, done by Micro Power Group Uganda Ltd on the site, established a design flow rate of 20litres per second at 50metres of head. A small concrete weir was proposed so as to provide sufficient depth of the water so that the penstock is fully submerged at all times. The natural storage area behind the weir would be enlarged by widening the river banks in order to guarantee sufficient storage even in dry seasons. This would ensure that the flow rate would normally be available throughout the year. At this flow, a locally fabricated pelton turbine coupled to an induction generator would be able to provide an electrical output capacity of 4.4kW, at an overall efficiency of 50% (Micro Power Group, 2010).

Also, Uganda's location along the equator, guarantees that the country receives some of the highest solar irradiation values in the world, through out the year. Photovoltaic systems (PV) are a proven technology, and numerous experiences around the world have proven their technical reliability and economic applicability in rural electrification programs (Denizar C. Martins, 2005). This presents an opportunity to utilize the available solar resources in this area for energy provision. Annualized solar radiation data is obtained from the NASA website as shown in figure 4 (NASA, 2004). As observed, Wanale has very good solar resources, receiving on average at least 5kWh/m^2/month average solar irradiation, with a maximum of over 6.5kWh/m^2/month. HOMER simulates the annualized average solar irradiation value at 5.94kWh/m^2/day.

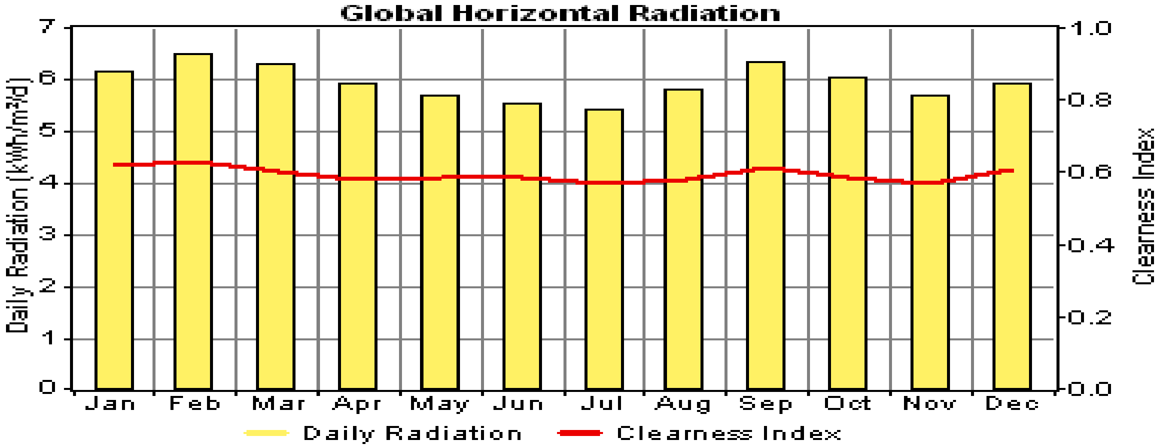


Figure 4: Solar irradiation data for Wanale village

4.2 The Electricity Demand

When determining the electricity consumption of any community, some of the factors to consider include; the income of consumers, their affordable tariff (price per kWh or monthly cost), cost of competing or substitute services (fuel-wood, kerosene), cost of appliances, socio-cultural and economic factors etc. Detailed planning methods must put into consideration all these factors, but despite the need to consider all these factors, the ability to get accurate information and the lack of recorded data, especially in rural areas are among the challenges faced by researchers and planners. Thus demand estimates are done based on the number of households and their assumed appliance use (Frances, 2002).

In the pre-feasibility analysis of the site, it was established that there existed about 80 households within a 1km radius in Wanale village with interest in this project who were ready to be connected once the system became operational. These also included a trading centre, with commercial activity and a dispensary among others. Though actual load forecasting consists of projecting peak demand requirements or energy consumption for the entire groups of customers, with the time period ranging from the short term (1-2 years) to the long term (3 years or more). In this study, an estimate of the short-term demand forecast at Wanale is done, based on consumption loads and patterns inferred from a model derived in the work done by (Blennow, 2004), for estimating electricity demand in rural villages in Tanzania as in figure 5.

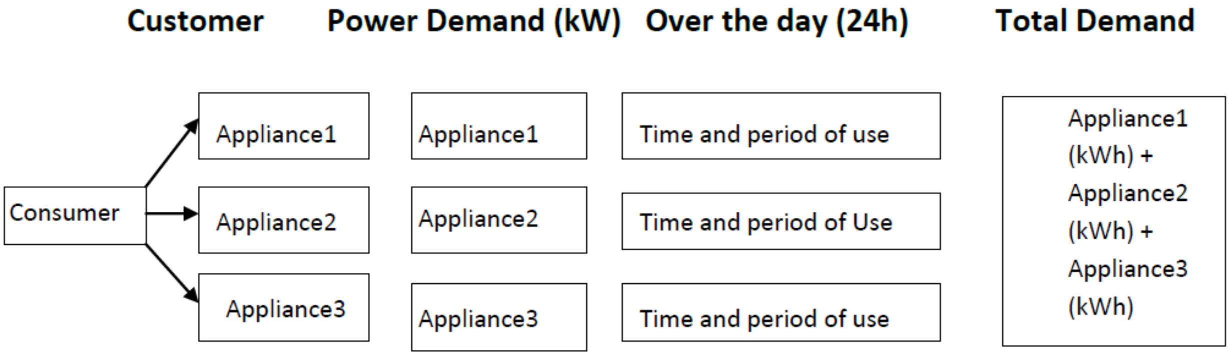


Figure 5: A description of the general idea for the demand modeling

In practice short-term load forecasting is affected by many factors such as weather conditions, daily, weekly and seasonal periodicity. It can, however, provide rough estimations of the loads, and estimate load profile. For Wanale's short-term demand forecast a set of generic disaggregated load profiles are generated based on:

- Typical rural residential consumption based on an assumption of lighting and small household appliances such as a radio, with a few consumers owning television sets, fridges and flat-irons in the short-term. Peak consumption is in the evening when all the lights and TV sets are switched on.
- Day time commercial activity based on the presence of small businesses in the trading centre, such as shops, restaurants, bars, video show centres, charging stations, and a dispensary.

4.2.1 Household residential load

Modeling the household load is based on the assumption that the number of appliances better reflect the consumption of electricity, as it is hard to get any accurate information about the income (Frances, 2002). Traditional cooking methods utilizing firewood and paraffin are expected to remain unchanged. This is due to the electricity expense associated with using modern cooking methods (boilers and cookers). Consumption patterns are thus derived based on ownership of appliances used for, lighting, communication (radio and TV, phone chargers), hot water, ironing and cooling (fridge).

It is assumed that in the short-term, the average electrified household will use 3 light bulbs, 2 indoor lights and 1 outdoor lamp for evening light (rural consumers are very conservative about outside lighting). The determining factor of the usage of light bulbs is the setting of the sun. Since Uganda is right along the equator, the time for dusk is very constant throughout the year. The internal light bulbs are thus turned on at around 7pm and turned off at around 11pm. It is assumed that at-least 50% of the households turn on their security lights daily from 7pm until 6 or 7am (Frances, 2002).

It is also assumed that at least 50% of the people use 1 radio of a small type, and by the end of the first year, each household will own at-least 1 small radio. Radios are used during varying hours of the day, but morning and evening hours are most common. News is a popular listening program, especially in the morning hours, thus it is assumed that most radios will be switched on early mornings for news broadcasts. Also taking the assumption that the women in most cases stay home during the day, at-least 50% of the radios would be in use during the day. During the evening hours not only the lights and radios are frequently used, but also TVs are then switched on (Frances, 2002). It is also assumed that the popularity of TV sets will rise rapidly, with at-least 50% of the population owning a television set within the first year.

It is expected that fridges will become popular in higher income households, with some fridges utilized for 24h, while others when needed. The electrical flat-iron is also expected to become a more common appliance as it replaces the charcoal heated iron, also electric water boilers (kettles) are expected to become popular especially in higher income households. Increased energy consumption may be anticipated on weekends as compared to the weekdays, mainly due to an increase in TV watching, radio listening and also the use of the flat-iron. But given that the flat-iron with a higher power rating of

1000W is normally used for short periods of time and at random intervals, its effect on the weekend load profile can therefore be considered as minimal (Frances, 2002).

4.2.2 Dispensary demand

A dispensary most likely to be found in a rural area, would be equipped enough to offer basic services in the form of first aid, some medication, and basic forms of treatment for common illnesses. Thus their estimated daily load would include: 2 indoor lamps, 2 security lamps, a 24h operating refrigerator, and a water boiler. Working hours are estimated to be between 7am and 10pm daily.

4.2.3 Commercial loads

Bars and restaurants

The load for the bars and restaurants is derived for light, music and a refrigerator for cooling soft drinks and alcoholic beverages. I assumed a bar and a restaurant to be almost equally equipped. A reasonable approximation would be that these establishments will acquire fridges in the short run. Thus the load for each bar or restaurant would comprise; 1 radio, 1 refrigerator, 1 indoor lamp, and 1 outdoor lamp; the restaurant will have a water boiler for preparing tea for consumers especially in the morning hours. The size of the radio for the bar and restaurant would though differ in general, big and small respectively. Also, the bar is assumed to have a bigger fridge for its capacity to store drinks. It is assumed that open hours for a bar are between 8am-11pm, while for a restaurant between 8am-8pm, with the fridges utilized for 24h. Another assumption would be that the bars will stay open longer on weekends.

Video show centers

This is a form of leisure activity common in many Ugandan rural settings. It can be categorized as a social recreation centre, where village members pay to watch movies, soccer and other televised programs. Expected load is based on: 1 TV, 1 video player, 1 refrigerator, 1 big radio for music and sound amplification, 1 indoor light and 2 outdoor/

security lights. Assumed operation is from 10 am to 10pm, except on weekends when they open earlier, at 8am.

Shops

In the shops, the electricity is utilized for lighting, refrigeration, a radio and smaller appliances such as phone charges. Generally in rural settings, the shop doubles as living quarters for the shop-owner. Of the electrified shops, it is assumed that 50% will own refrigerators for cooling drinks. Working hours are assumed to be from 7am to 10pm daily.

Barbershop and Hairdresser

Saloon services are an essential service for the community. Expected demand is based on: 2 inside fluorescent lamps, 1 outside lamps, 2 small hair driers for the hair dressers, 2 racers for the barbers, and a small radio. Working hours for the saloon would be from 8am to 8pm.

Fuel pump

A fuel pump can also be anticipated as a commercial activity in the trading centre. This supplies the community with paraffin (for cooking and lighting), and also petrol for the 'bodabodas' (commercial motorcycle transportation). It includes two pumps, for kerosene and petro, a small radio for the attendant, and a security lamp. Estimated hours of operation are between 7am-6pm daily.

The above mentioned loads are used to generate an estimate of the would-be hourly daily demand at Wanale. A total load profile is then generated to represent the estimated annual short-term load profile. This is simulated in HOMER software to take on the shape as shown in figure 6. This presents Wanale's daily demand at 144kWh, with a peak load of 14kW.

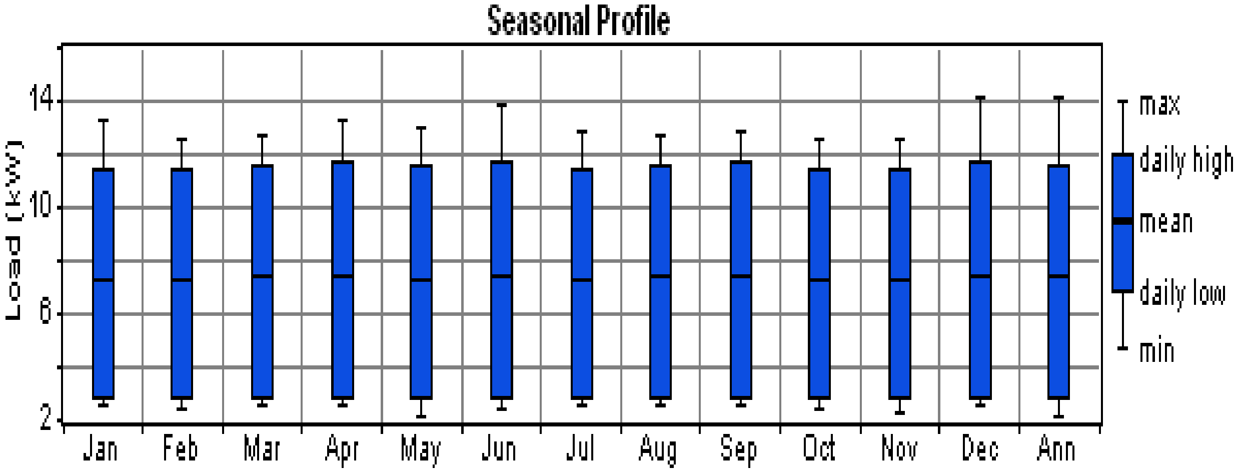


Figure 6: Wanale load profile

As can be observed, this load is greater than the available supply capacity from the design supply of the Pico-hydro plant. Thus in this study, different supply configurations are going to be investigated to determine the optimal supply system to meet the electricity demand at Wanale village. Electricity supply will be based on available resources for hydro and solar. Also included in the design will be battery energy storage, and a diesel generator. The objective is to achieve the most reliable system at the least Cost of Energy.

4.3 Hybrid Mini-grid System Architecture

In the design of a mini-grid system, the choice and sizing of the components, and the most adequate control and management strategy must be obtained (B.K Bala & Saiful Azam Siddique, 2009). Numerous configurations of hybrid energy systems have been installed in a variety of countries over the last three decades. This has provided the necessary experience to identify the strengths and weaknesses of different configurations. Thus good performance models have been developed, that are able to prioritize the functionality of the power supply systems in such a way as to achieve cost reductions and improve system reliability. Hybrid power systems can be categorized according to their configurations (HYRESS, 2008):

4.3.1 Series configuration:

In this configuration, shown in figure 7w, all the electricity goes through the battery. The inverter then converts the DC power from the battery for delivery to the AC load (HYRESS, 2008).

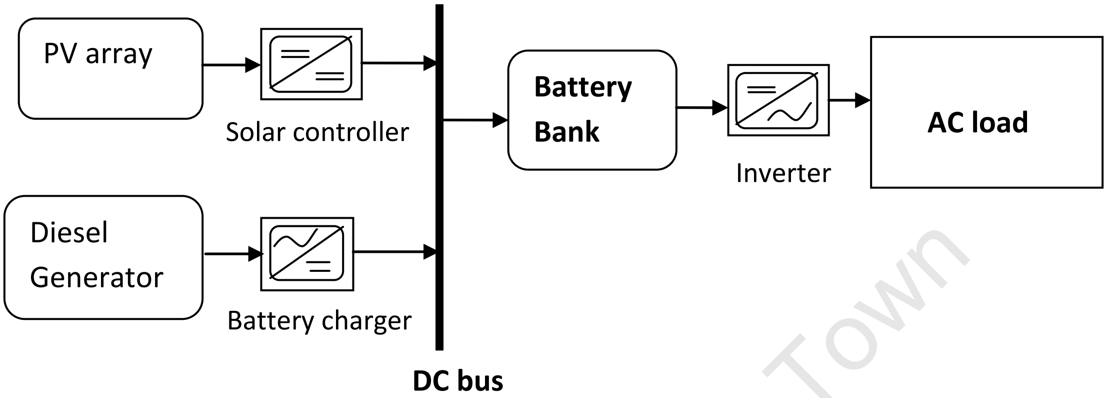


Figure 7: Series PV-diesel hybrid system

The simplified electrical output interface makes this one of the most common configurations, especially in Solar Home Systems (SHS). The disadvantages though to this system are;

- Both the diesel generator and the inverter have to be sized to meet peak loads; this can result in system over-sizing and or redundant operation.
- The frequent cycling of the batteries shortens the battery life;
- Also, there're increased conversion losses with the power generated by the diesel generator first rectified and then inverted back to meet the AC load;
- And system operation is dependent upon the inverter, with failure leading to overall break down.

4.3.2 Switched Configuration

In this configuration as shown in figure 8, the diesel generator and the PV can charge the battery bank, as well as supply the AC load (through the inverter for the PV array). The main advantage to this system is that the generator can supply the load directly (thus higher overall efficiency than the series configuration) as well as charge the batteries, while during periods of low demand, it can be switched off, and the supply switched to the battery bank and the PV array (through the change-over switch). With the generator designed as an independent supply system from the PV and battery bank, it is incapable of topping up to the battery and PV supply when demand requires it. Thus the system is designed to either be supplied by the generator or by the PV and battery.

In this configuration, system operation can be manual, although the complexity of the system can be simplified through automation (HYRESS, 2008).

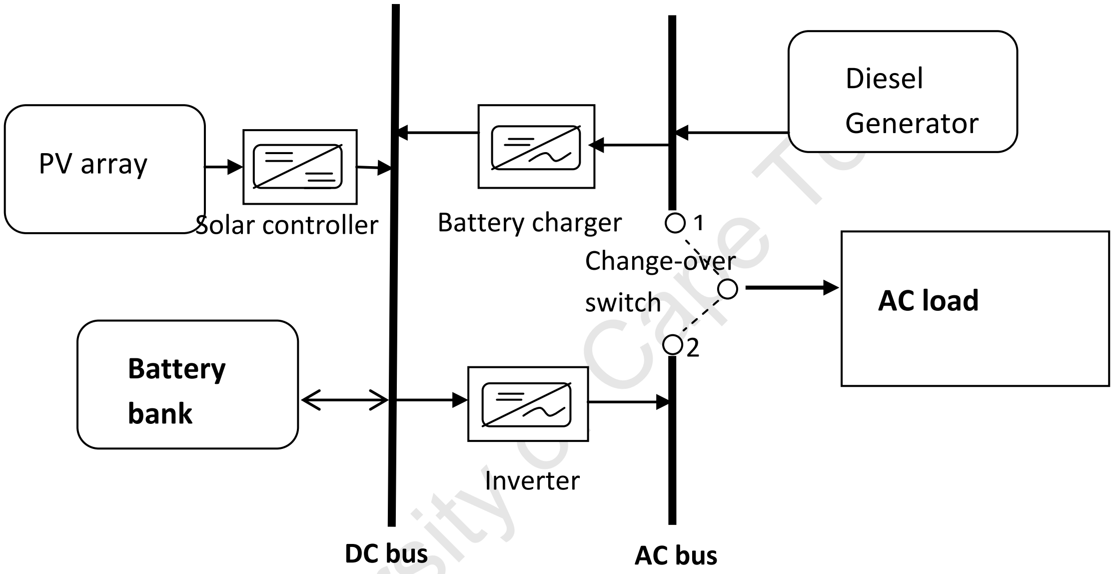


Figure 8: Switched PV-diesel hybrid system

The main disadvantages to this system are that;

- During the switch change-over, power supply will always be momentarily disrupted;
- Also, with the generator directly coupled, and thus designed to meet the peak AC load, at part-load operation, the efficiency of the generator will be compromised.

4.3.3 Parallel Configuration

Current hybrid energy system software simulations and designs are based on this model design as shown in figure 9. The parallel configuration allows all energy sources to supply the loads separately depending on the demand, as well as meeting an increased level of demand by combining the various energy sources. The bi-directional inverter charges the battery (acting as a rectifier) when excess energy is available from the other generators, as well as act as DC-AC converter (inverter) under normal operation. The integration of an assortment of energy generation components and storage mechanisms is very complex. Therefore these objectives can only be met if the interactive operation of the individual generators and associated components is controlled by a dynamic energy management system. The main advantage of this system is improved system efficiency and reliability through optimal operation and sizing of the generation components to meet the demand. While the main disadvantages to this system are, its complexity, and thus the need to automate the different controls; and also specialized training to operate the system (HYRESS, 2008).

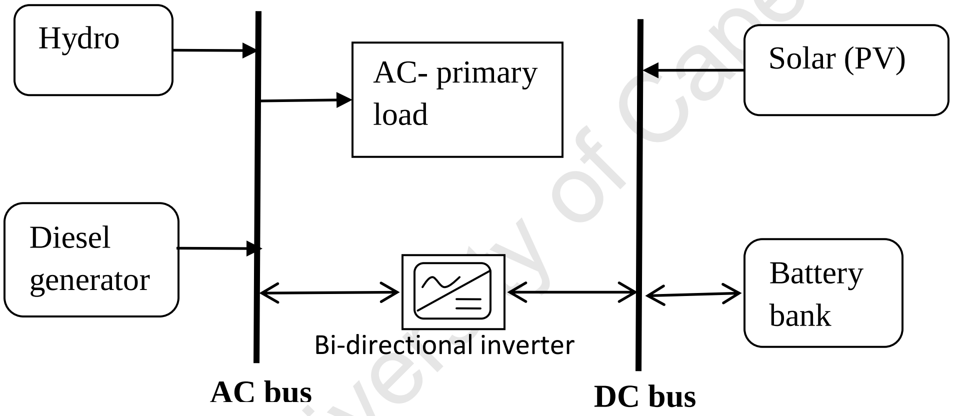


Figure 9: 'Parallel' Hydro-PV-Battery-Diesel hybrid system as simulated in HOMER

4.4 Hybrid Mini-grid System Design

Through software modeling, theoretical planning and analysis of the behavior of a rural electrification system can be done (Tommer Ender, 2008). In this study, HOMER software is used to size and simulate the different supply configurations and performance elements of the hybrid mini-grid system design. The system configuration used by HOMER for the design simulations is based on the "parallel" architecture, shown in figure 9.

4.4.1 System inputs

System analysis with HOMER requires information on the resources, economic constraints, and control methods. Input information will include: village demand (one year of load data), renewable resources, component technical details and costs, constraints, controls, type of dispatch strategy.

In the table below is the cost and technical information for the Wanale hybrid mini-grid system design. Preliminary studies done by Micro Power Group establish the Pico-hydro plant to an output of 4.4kW. Initial capital cost estimates for small hydro plants internationally, with current technologies, can range from US$ 1,500 to $2,500/kW (K. Kusakana, et al., 2009). With 75% of the development cost determined by the location and site conditions, and 25% being the cost of the manufactured electrical and mechanical components (RETScreen, 2004). In this study, the cost was taken at $2,500/kW because of the location, and terrain of the village. The component cost information is shown in table 1. Technical and cost information for PV, diesel, converter and battery is referred from (Akyuz, et al., 2010) and (Rolland Simon & Guido Glanio, 2011)

Table 1: Technical and cost data considered for the hybrid energy system.

System	**Parameter**	**Unit**
PV	Capital cost (U.S $/kWp)	2,822
	Replacement cost (U.S $/kWp)	2,822
	Operation & maintenance ($/yr)	0
	Life time (yr)	25
Hydro	Available head (m)	45.29
	Design flow rate (L/s)	20

	Efficiency (%)	50
	Capital cost (U.S $)	11,000
	Operation & Maintenance ($/yr)	90
Diesel generator	Capital cost (U.S $/kW)	400
	Replacement cost (U.S $/kW)	400
	Operation & maintenance ($/hr)	0.15
	Life time (year)	10
	Diesel price (U.S $/l)	1.33
Converter	Capital cost(U.S $/kW)	1,445
	Replacement cost (U.S $/kW)	1,445
	Operation & maintenance ($/yr)	0
	Life time (yr)	15
	Efficiency (%)	90
Battery storage (Ah)	Type	6FM200D
	Capital cost (U.S $/unit)	800
	Replacement cost (U.S $/unit)	600
	Operation & maintenance ($/yr)	15
	Project life time (years)	25
	Annual real interest rate (%)	8

4.4.2 Case 1: Pico-hydro supply

Mini-grid systems for rural electrification should be configured to supply power to the consumers in the most economic way achievable, but also to satisfy the demand. The presence of hydro resources at Wanale guarantees a baseload supply of electricity, but as shown in figure 11, the capacity would not be enough to cater for the projected short-term village demand, thus consideration of other resources.

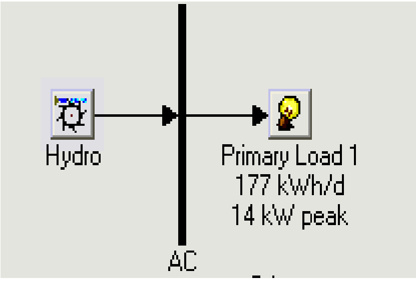
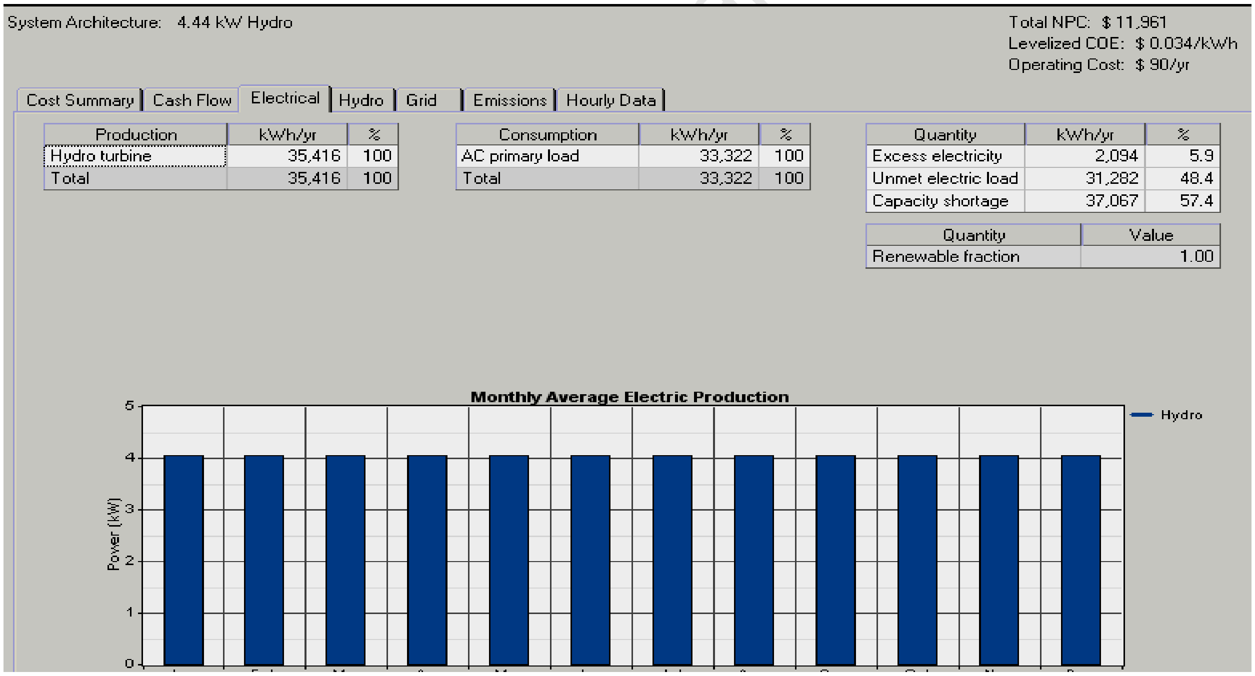


Figure 10: HOMER mini-grid model for hydro supply


System Architecture: 4.44 kW Hydro

Total NPC: $ 11,961
Levelized COE: $ 0.034/kWh
Operating Cost: $ 90/yr

Production	kWh/yr	%
Hydro turbine	35,416	100
Total	35,416	100

Consumption	kWh/yr	%
AC primary load	33,322	100
Total	33,322	100

Quantity	kWh/yr	%
Excess electricity	2,094	5.9
Unmet electric load	31,282	48.4
Capacity shortage	37,067	57.4

Quantity	Value
Renewable fraction	1.00

Figure 11: System electrical supply properties

With only the Pico-hydro supplying electricity, the system incurs a capacity shortage of over 57%, meeting less than half of the village's annual demand. Therefore this system is insufficient to meet the demand, and additional generators and resources are required to match the load.

Therefore, three other possible supply configurations are simulated based on the consideration of all possible available generation resource options.

4.4.3 Case 2: Hydro + diesel generator

In this configuration, the Pico-hydro plant provides the baseload electricity supply, while a diesel generator is designed with the system to provide the additional energy supply when necessary. This configuration offers the more simplified generation system, and this has been a configuration of choice in many mini-grid installations involving small hydro systems.

The system design and operational characteristics as modeled in HOMER are as shown in the figures 12-15. And as shown in figure 13, the optimal system design would include the addition of a 10kW diesel generator to the 4.4kW Pico-hydro supply, at an initial system cost of $ 15,000. At a diesel price 1/litter, the Total Net Present Cost (TNPC) accumulates to $ 271,609, resulting in a system levelized energy cost of **$0.394/kWh**.

It is also observed in figure 13 that although the hydro cost is the dominant initial capital cost, the diesel generators lifecycle costs are significantly higher, mainly due to the operation and fuel costs.

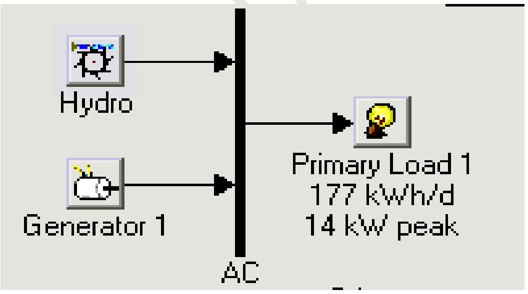
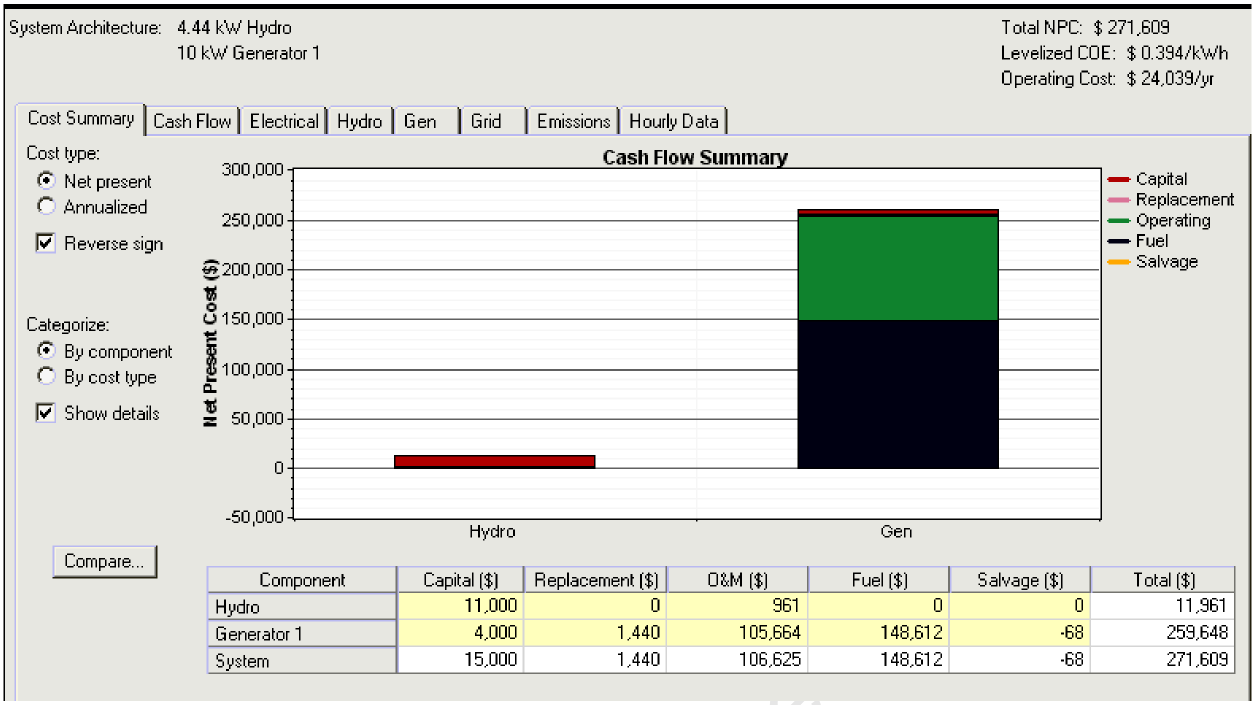


Figure 12: HOMER hybrid mini-grid system configuration



System Architecture: 4.44 kW Hydro
10 kW Generator 1

Total NPC: $ 271,609
Levelized COE: $ 0.394/kWh
Operating Cost: $ 24,039/yr

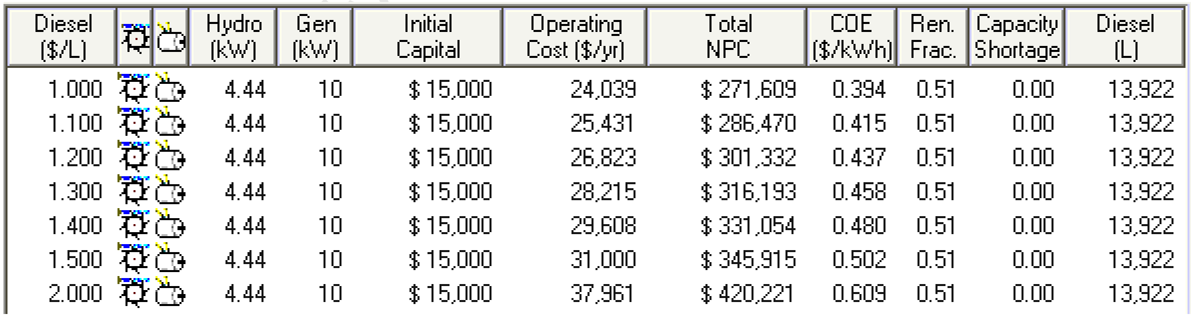
Cost type:
● Net present
○ Annualized
☑ Reverse sign

Categorize:
● By component
○ By cost type
☑ Show details

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Hydro	11,000	0	961	0	0	11,961
Generator 1	4,000	1,440	105,664	148,612	-68	259,648
System	15,000	1,440	106,625	148,612	-68	271,609

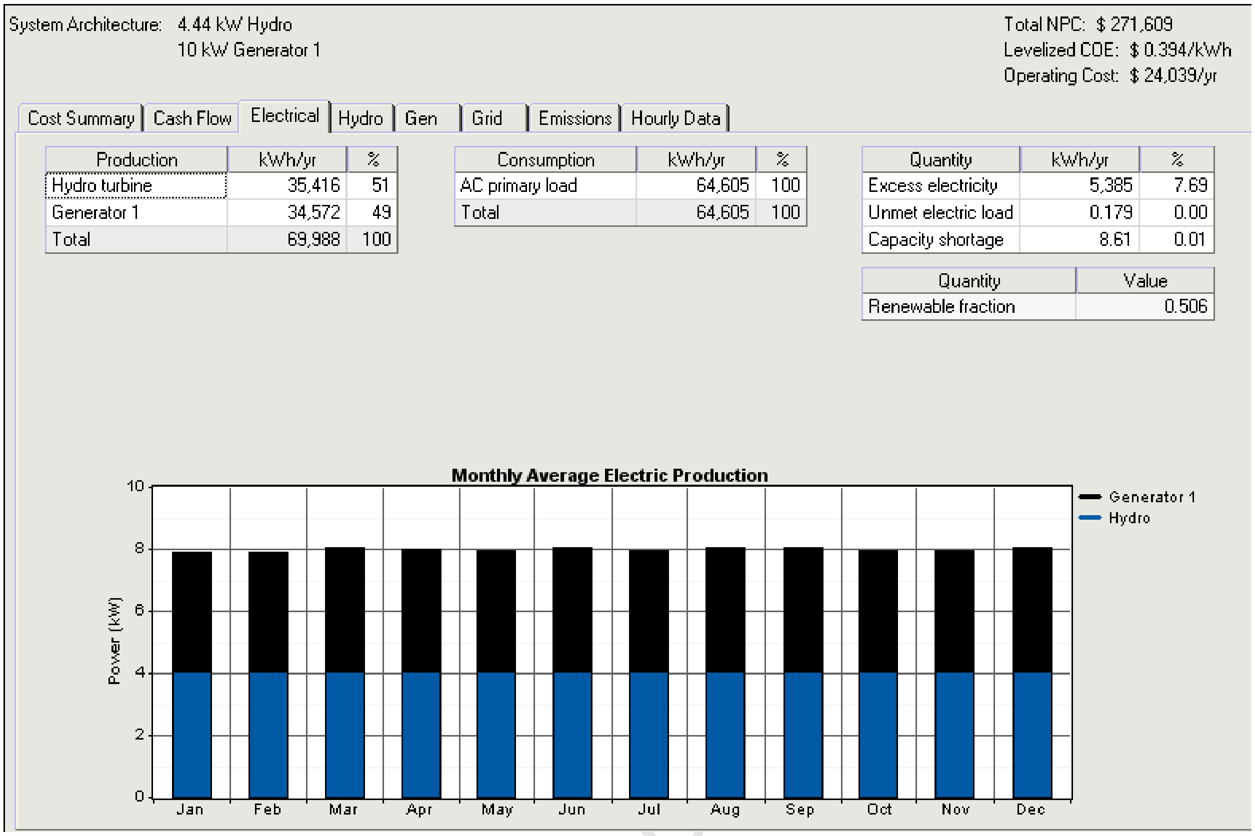
Figure 13: System cash flow analysis

As observed in the sensitivity analysis in figure 14, with the cost of fuel rising, the operating costs of the system will also increase, resulting in higher energy costs. It is also observed in the electrical supply properties in figure 15 that the system supply matches the demand perfectly incurring no capacity shortages, with a small percentage of excess energy.



Diesel ($/L)			Hydro (kW)	Gen (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)
1.000			4.44	10	$ 15,000	24,039	$ 271,609	0.394	0.51	0.00	13,922
1.100			4.44	10	$ 15,000	25,431	$ 286,470	0.415	0.51	0.00	13,922
1.200			4.44	10	$ 15,000	26,823	$ 301,332	0.437	0.51	0.00	13,922
1.300			4.44	10	$ 15,000	28,215	$ 316,193	0.458	0.51	0.00	13,922
1.400			4.44	10	$ 15,000	29,608	$ 331,054	0.480	0.51	0.00	13,922
1.500			4.44	10	$ 15,000	31,000	$ 345,915	0.502	0.51	0.00	13,922
2.000			4.44	10	$ 15,000	37,961	$ 420,221	0.609	0.51	0.00	13,922

Figure 14: Fuel price sensitivity analysis



System Architecture: 4.44 kW Hydro
10 kW Generator 1

Total NPC: $ 271,609
Levelized COE: $ 0.394/kWh
Operating Cost: $ 24,039/yr

Production	kWh/yr	%
Hydro turbine	35,416	51
Generator 1	34,572	49
Total	69,988	100

Consumption	kWh/yr	%
AC primary load	64,605	100
Total	64,605	100

Quantity	kWh/yr	%
Excess electricity	5,385	7.69
Unmet electric load	0.179	0.00
Capacity shortage	8.61	0.01

Quantity	Value
Renewable fraction	0.506

Figure 15: Hydro-diesel system electrical supply properties

4.4.4 Case 3: Hydro + Solar + energy storage

In this configuration, hydro provides the baseload electricity supply, while with the available solar resources in the village, while the system is also designed to utilize the available solar resources in the village and thus incorporate PV in the electricity supply system. The intermittence of supply from the solar resource demands the presence of an energy storage facility for improved system reliability. This is simulated in HOMER in the form of Absorbent Glass Mat (AGM) sealed deep-cycle lead-acid batteries.

The hybrid mini-grid system design and operational characteristics are as shown in figures 16-19 below.

As shown in figure 17, the optimal design is sized at, in addition to the 4.4kW supply from hydro, an additional 8kW from PV, with a 4 battery bank energy storage facility (9.6kWh nominal capacity).

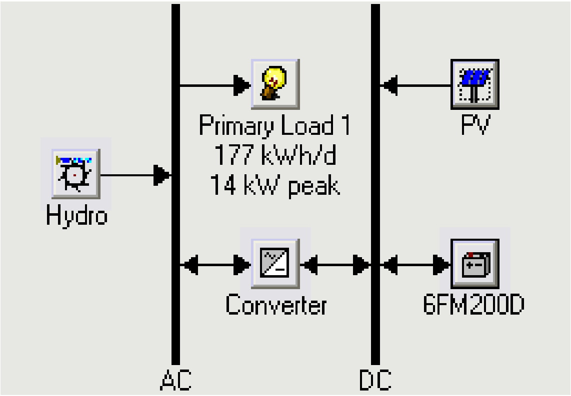


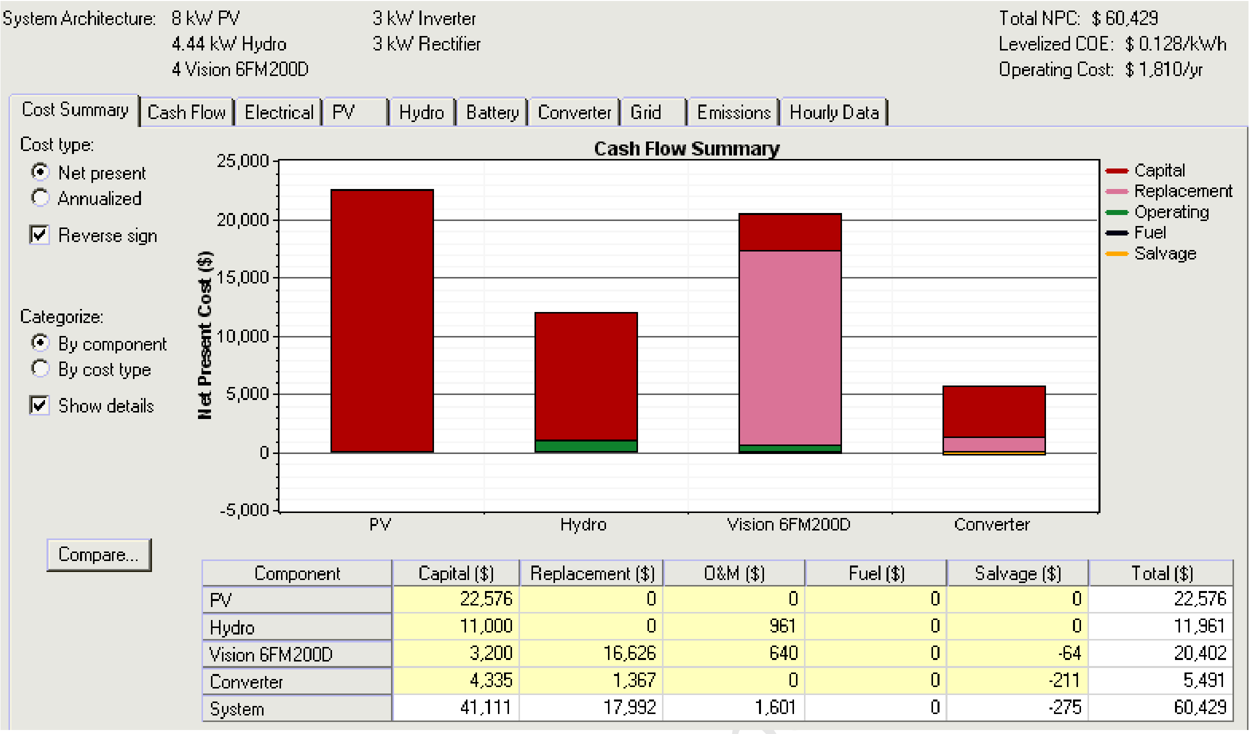
Figure 16: HOMER hybrid mini-grid system configuration

	PV (kW)	Hydro (kW)	6FM200D	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
	8	4.44	4	3	$ 41,111	1,810	$ 60,429	0.128	1.00	0.40

Figure 17: HOMER results analysis

It is shown in the cash flow analysis in figure 18, that this system has a higher initial cost than the system in case 2 due to the cost of the PV panels. The replacement costs are dominated by the battery replacements. This system though offers lower life cycle costs compared to case 2, at a Total Net Present Cost of $ 60,429 resulting in an energy cost of **$0.128/kWh**.

The biggest draw back to this system is its insufficiency in meeting the total demand. This is observed in the electrical supply properties in figure 19, with the system incurring a 40% capacity shortage.

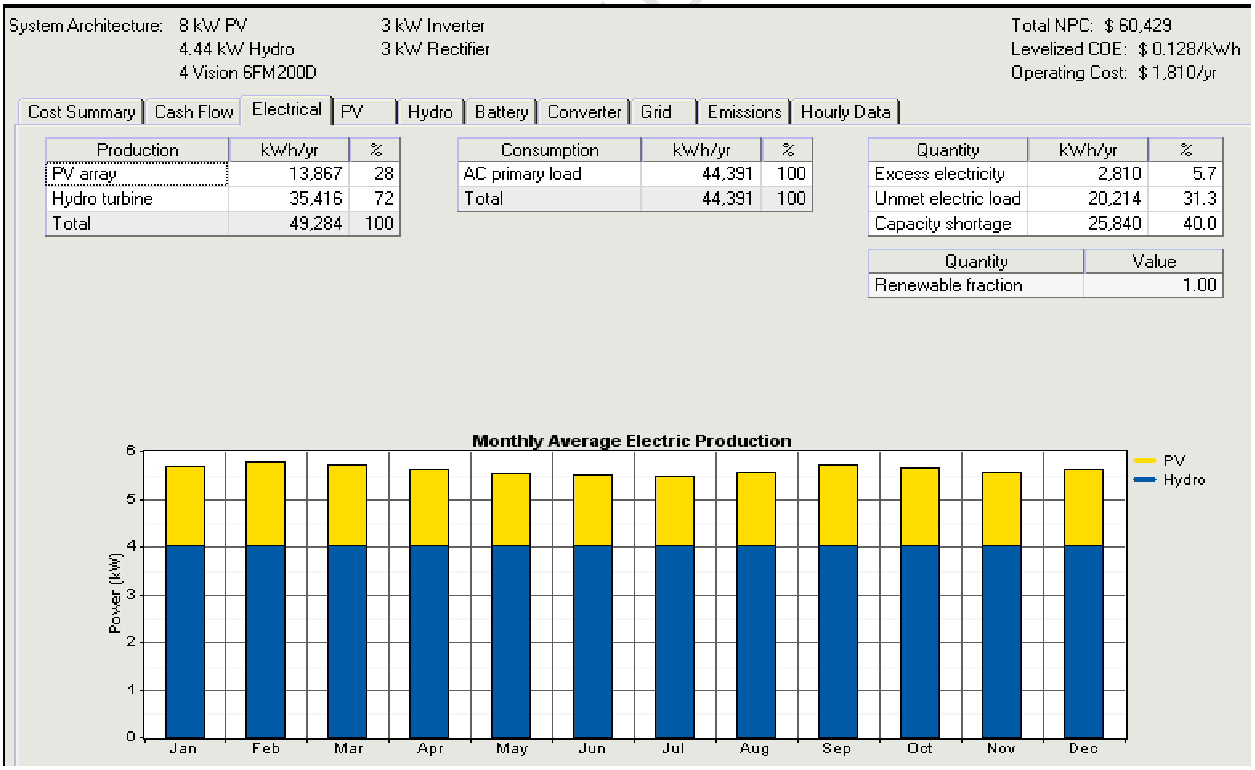


System Architecture: 8 kW PV; 4.44 kW Hydro; 4 Vision 6FM200D; 3 kW Inverter; 3 kW Rectifier

Total NPC: $ 60,429
Levelized COE: $ 0.128/kWh
Operating Cost: $ 1,810/yr

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	22,576	0	0	0	0	22,576
Hydro	11,000	0	961	0	0	11,961
Vision 6FM200D	3,200	16,626	640	0	-64	20,402
Converter	4,335	1,367	0	0	-211	5,491
System	41,111	17,992	1,601	0	-275	60,429

Figure 18: System cash flow analysis



System Architecture: 8 kW PV; 4.44 kW Hydro; 4 Vision 6FM200D; 3 kW Inverter; 3 kW Rectifier

Total NPC: $ 60,429
Levelized COE: $ 0.128/kWh
Operating Cost: $ 1,810/yr

Production	kWh/yr	%
PV array	13,867	28
Hydro turbine	35,416	72
Total	49,284	100

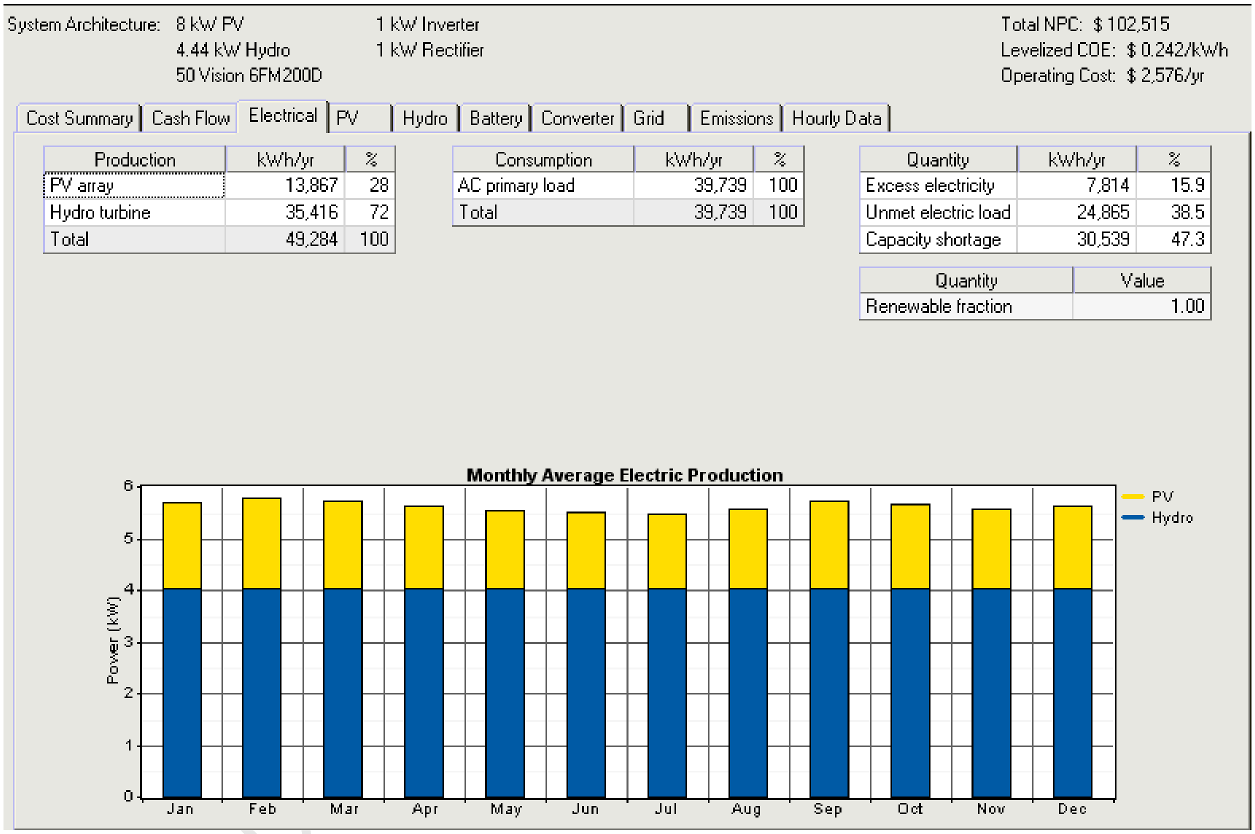
Consumption	kWh/yr	%
AC primary load	44,391	100
Total	44,391	100

Quantity	kWh/yr	%
Excess electricity	2,810	5.7
Unmet electric load	20,214	31.3
Capacity shortage	25,840	40.0

Quantity	Value
Renewable fraction	1.00

Figure 19: Hydro-PV-battery system electrical supply properties

A sensitivity analysis on the battery sizes is simulated in HOMER to increase the energy storage capacity of the system, but even at an overwhelming battery storage capacity of 120kWh (50 batteries), optimal system operation will always incur a capacity shortage, increasing to 47% as shown in figure 20. This is due to the intrinsic nature of the solar resources, thus the supply does not meet the demand, and further simulations do not change the outcome.


System Architecture: 8 kW PV
4.44 kW Hydro
50 Vision 6FM200D
1 kW Inverter
1 kW Rectifier

Total NPC: $ 102,515
Levelized COE: $ 0.242/kWh
Operating Cost: $ 2,576/yr

Production	kWh/yr	%
PV array	13,867	28
Hydro turbine	35,416	72
Total	49,284	100

Consumption	kWh/yr	%
AC primary load	39,739	100
Total	39,739	100

Quantity	kWh/yr	%
Excess electricity	7,814	15.9
Unmet electric load	24,865	38.5
Capacity shortage	30,539	47.3

Quantity	Value
Renewable fraction	1.00

Figure 20: Hydro-PV-battery supply characteristics, with 50 batteries

4.4.5 Case 4: Hydro + Solar +energy storage + Diesel

In this configuration, the system utilizes all available generator options, with a diesel generator added in the mix to provide backup supply, to the hydro, PV and energy storage. System design and operational characteristics are as shown in figures 21-24.

As shown in figure 22, the hybrid mini-grid system, in addition to the 4.4kW supply from hydro, would include a 7kW PV array supply, a 5kW diesel backup generator and a 24 battery (AGM deep-cycle lead-acid battery) energy storage facility (57.6kWh nominal capacity).

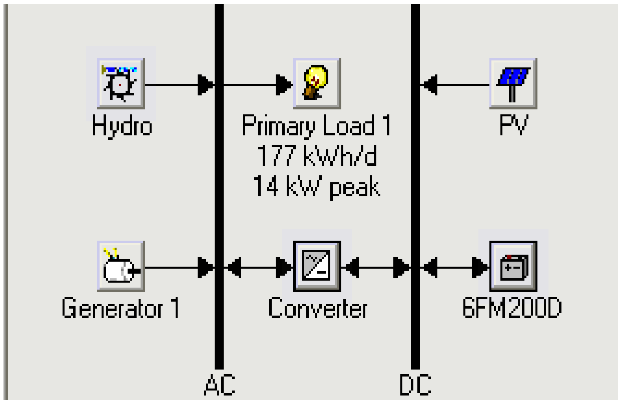
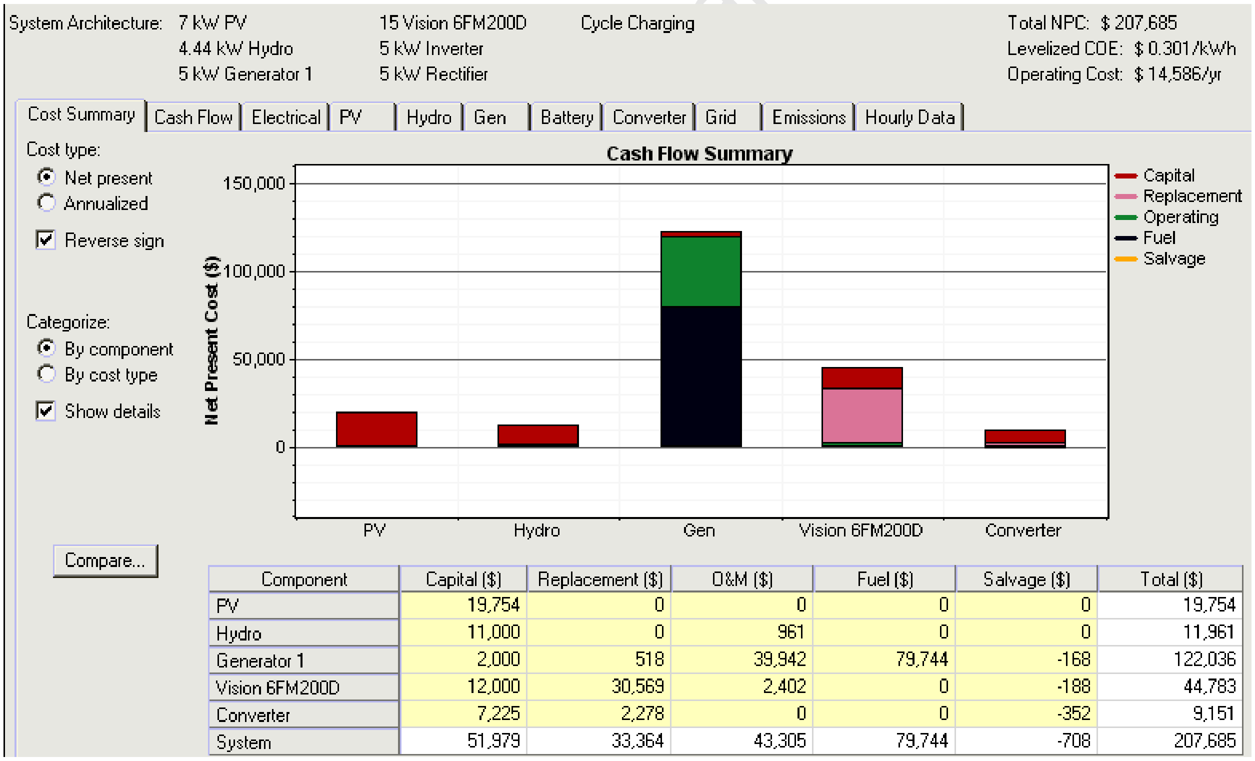


Figure 21: HOMER hybrid mini-grid system configuration



System Architecture: 7 kW PV; 4.44 kW Hydro; 5 kW Generator 1; 15 Vision 6FM200D; 5 kW Inverter; 5 kW Rectifier; Cycle Charging

Total NPC: $ 207,685
Levelized COE: $ 0.301/kWh
Operating Cost: $ 14,586/yr

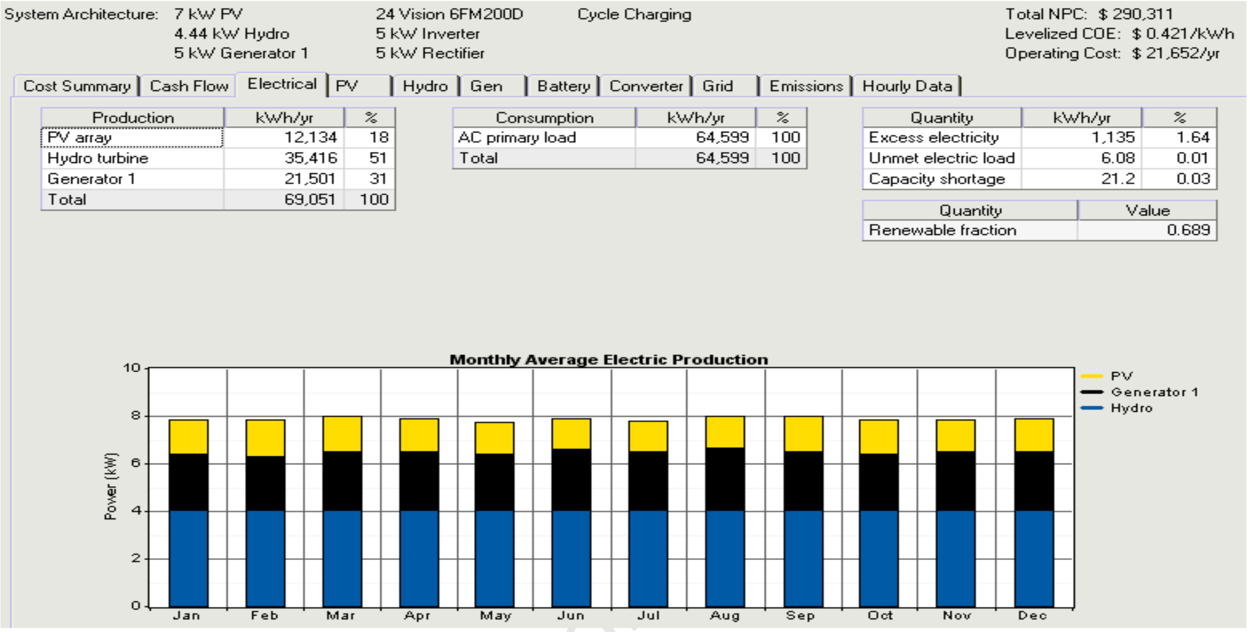
Cost type:
● Net present
○ Annualized
☑ Reverse sign

Categorize:
● By component
○ By cost type
☑ Show details

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	19,754	0	0	0	0	19,754
Hydro	11,000	0	961	0	0	11,961
Generator 1	2,000	518	39,942	79,744	-168	122,036
Vision 6FM200D	12,000	30,569	2,402	0	-188	44,783
Converter	7,225	2,278	0	0	-352	9,151
System	51,979	33,364	43,305	79,744	-708	207,685

Figure 22: System cash flow analysis

As observed in the cash flow analysis in figure 22, the hydro incurs the higher capital cost, while the replacement costs of the batteries contribute significantly to their life cycle costs, and as observed the operation and fuel costs of the diesel generator dominate the system life cycle costs. Thus at a system initial capital cost of $ 51,979 the Total Net Present Costs (TNPC) accumulate to $ 207,685, resulting in a system levelized energy cost of **$0.301/kWh**, for the price of diesel at $ 1/litter.



System Architecture: 7 kW PV, 4.44 kW Hydro, 5 kW Generator 1, 24 Vision 6FM200D, 5 kW Inverter, 5 kW Rectifier, Cycle Charging

Total NPC: $ 290,311
Levelized COE: $ 0.421/kWh
Operating Cost: $ 21,652/yr

Production	kWh/yr	%
PV array	12,134	18
Hydro turbine	35,416	51
Generator 1	21,501	31
Total	69,051	100

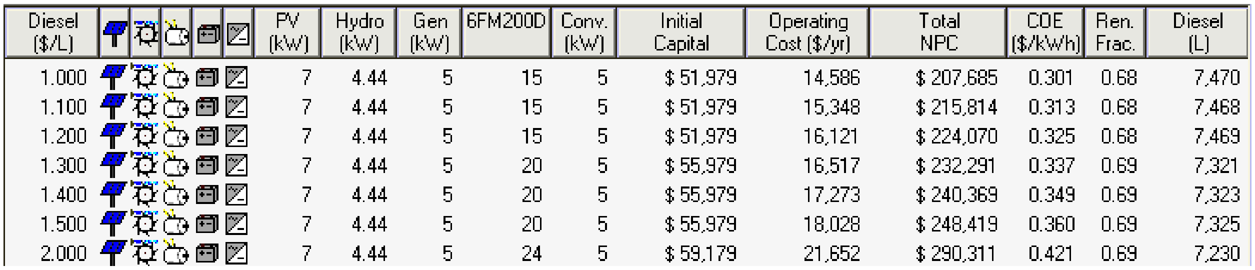
Consumption	kWh/yr	%
AC primary load	64,599	100
Total	64,599	100

Quantity	kWh/yr	%
Excess electricity	1,135	1.64
Unmet electric load	6.08	0.01
Capacity shortage	21.2	0.03

Quantity	Value
Renewable fraction	0.689

Figure 23: Hydro-PV-diesel-battery system electrical supply properties

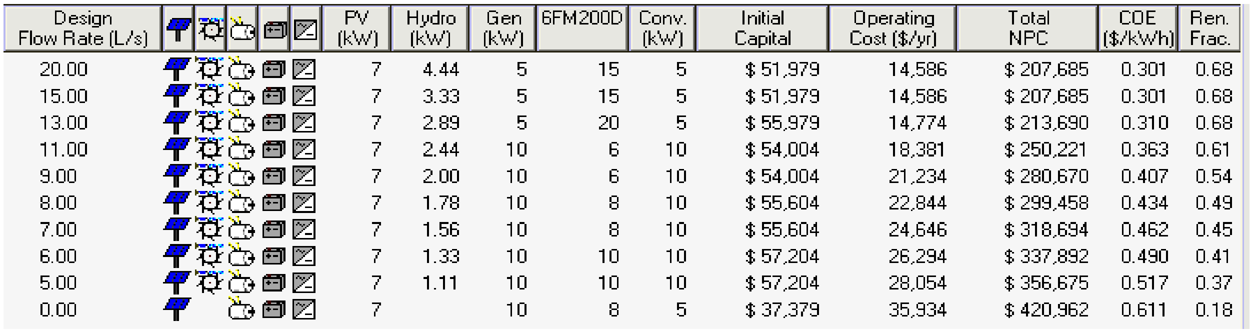
It is also observed in the electrical supply properties in figure 23 that this system matches the demand perfectly with no capacity constraints. Also a sensitivity analysis done on the rising cost of fuel has a slightly smaller effect on the energy cost compared to the system in case 3.



Diesel ($/L)	PV (kW)	Hydro (kW)	Gen (kW)	6FM200D	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)
1.000	7	4.44	5	15	5	$ 51,979	14,586	$ 207,685	0.301	0.68	7,470
1.100	7	4.44	5	15	5	$ 51,979	15,348	$ 215,814	0.313	0.68	7,468
1.200	7	4.44	5	15	5	$ 51,979	16,121	$ 224,070	0.325	0.68	7,469
1.300	7	4.44	5	20	5	$ 55,979	16,517	$ 232,291	0.337	0.69	7,321
1.400	7	4.44	5	20	5	$ 55,979	17,273	$ 240,369	0.349	0.69	7,323
1.500	7	4.44	5	20	5	$ 55,979	18,028	$ 248,419	0.360	0.69	7,325
2.000	7	4.44	5	24	5	$ 59,179	21,652	$ 290,311	0.421	0.69	7,230

Figure 24: Sensitivity analysis on the fuel price

The drawback to this system would be a seasonally varying flow-rate. A sensitivity analysis on the design flow-rate is presented in figure 25.



Design Flow Rate (L/s)	PV (kW)	Hydro (kW)	Gen (kW)	6FM200D	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
20.00	7	4.44	5	15	5	$ 51,979	14,586	$ 207,685	0.301	0.68
15.00	7	3.33	5	15	5	$ 51,979	14,586	$ 207,685	0.301	0.68
13.00	7	2.89	5	20	5	$ 55,979	14,774	$ 213,690	0.310	0.68
11.00	7	2.44	10	6	10	$ 54,004	18,381	$ 250,221	0.363	0.61
9.00	7	2.00	10	6	10	$ 54,004	21,234	$ 280,670	0.407	0.54
8.00	7	1.78	10	8	10	$ 55,604	22,844	$ 299,458	0.434	0.49
7.00	7	1.56	10	8	10	$ 55,604	24,646	$ 318,694	0.462	0.45
6.00	7	1.33	10	10	10	$ 57,204	26,294	$ 337,892	0.490	0.41
5.00	7	1.11	10	10	10	$ 57,204	28,054	$ 356,675	0.517	0.37
0.00	7		10	8	5	$ 37,379	35,934	$ 420,962	0.611	0.18

Figure 25: Sensitivity analysis on the design flow rate

It is observed that below a flow rate of 15liters per second for the Pico-hydro plant, the cost of energy begins to rise. This is due to the increased use of the generator to provide the additional supply.

4.4.6 Results discussion analysis

Four configurations of the proposed power supply system for Wanale village have been simulated, each with its advantages and disadvantages. Below is a summary of the findings.

- The Pico-hydro system in case 1 has insufficient capacity to meet the supply, thus additional generation options were required to achieve optimal operation in meeting the village demand

- The system utilizing an additional diesel generator to the hydro supply in case 2 offers a more simplified configuration, which is the initially cheaper solution. But given that its levelized energy cost is dependent upon the price of fuel, with the instability in fuel prices and other related issues, even at a conservative cost of $1/litre of fuel, the energy cost is still higher in comparison to the other configurations. And as observed in figure 14, the energy price will rise with the fuel cost.

- The system in case 3 utilizing hydro, solar + battery energy storage offers the overall least energy cost, but its capacity to meet the village demand is limited, and thus power distribution to the consumers would be unreliable. Even when the system is simulated with a much larger size battery storage capacity as shown in figure 20, the system still incurs a capacity shortage of over 47%. At this point the system is also shown to produce over 16% excess energy. This indicates that the resources are not matched to the energy storage, and further simulation does not change this situation.

- The mini-grid system in case 4, utilizing hydro, solar + energy storage, + a diesel generator finds the best balance in operation, meeting the village demand at a significantly low energy cost. Even at increasing fuel prices, the Levelized energy cost remains within a comfortable range as shown in figure 24 compared to the cost changes in case 2. With the only operational draw back being the variation in the design flow rate as shown in figure 25. Also, because the diesel generator in the system in case 4 is used less frequently than in case 2, the operating costs are reduced through improved system efficiency resulting in a reduction in fuel consumption, and thus reduced emission levels. The system gas emission comparisons are as shown in table 2.

Table 2: Emissions comparisons

	Hydro + Solar + Battery	Hydro + Diesel	Hydro + Solar + Battery + Diesel
Pollutant	Emissions (kg/yr)		
Carbon dioxide	0	36,661	19,672
Carbon monoxide	0	90.5	48.6
Unburned hydrocarbons	0	10	5.38
Particulate matter	0	6.82	3.66
Sulfur dioxide	0	73.6	39.5
Nitrogen oxides	0	807	433

In conclusion, the hybrid mini-grid system configuration in case 4 offers operational and financial superiority to the other configurations and is thus the proposed mini-grid system for meeting the demand at Wanale village. This system has the potential to provide clean and reliable electricity for meeting the energy needs of the residents of Wanale village.

4.4.7 System operation strategy

The role of the control system in managing the energy flow of the system is essential to achieving reliability in operation. The following operating strategy is therefore employed for the hybrid mini-grid system (Gupta, et al., 2008).

I. The electricity generators are loaded in order of increasing unit generation cost (hydro then PV then diesel);

II. If the renewable generators are unable to supply the hourly total demand, then the battery bank and diesel generator will be loaded respectively for additional supply.

The use of electric power generated by hydro, then PV has priority in satisfying the electric demand over any other component in the system. Hydro provides the baseload supply of electricity. But if the total electric power generated by the hydro and PV generators exceeds the demand, then additional electric power will be used to charge the batteries. When the batteries are fully charged, the remaining electric power is disposed off to a thermal load. If the renewable energy is insufficient to satisfy the demand, electric power will be discharged from the batteries to supply the demand. If the batteries cannot satisfy the demand, then the diesel generator is dispatched to cater for the excess demand. Also, battery discharging continues until a minimum battery state of charge (SOC) which should not fall below 40%, and then the diesel generator has to pick up the slack. The diesel generator is operated in the cycle charging strategy, where it runs at power enough to cover the net-load demand while simultaneously charging the batteries until they are full (Pradeep. K. Katti, 2005).

4.4.8 Cost analysis

The current electricity tariff for residential consumers connected to the main electricity grid in Uganda is Ush.385/kWh (Kasita, 2010). At a current average exchange rate of 1:2500 USD to Ush this is = $0.154/kWh. At a mini-grid energy cost of $0.301/KWh = Ush.752.5/kWh. This energy cost is too high for a rural consumer in Uganda to afford without any form of support.

The biggest contribution to the energy cost is the initial capital investment of the system. A number of funding schemes have been proposed in various publications especially for the support of renewable energy technologies. Some of these include the Renewable energy Premium Tariff (RPT) and the Global Energy Transfer Feed-in Tariff (GET-FiT) (Moner-Girona, 2008), (Fulton, 2010). These can be used to fully or partially subsidize the system capital costs.

With capital cost subsidies on the renewable energy generators, the effect on the cost of energy of the system is shown in figure 25 below. And as illustrated, the subsidy effect on the capital cost of solar alone does not offer a substantial change to the energy cost, while a subsidy on the hydro has a more pronounced effect. It is also shown that a 100% subsidy on the capital costs of hydro and solar drops the energy cost to as low as $0.26/kWh. Further subsidies on the fuel costs of the diesel generator can achieve an even lower energy cost, thus enabling the system's push towards financial sustainability. With additional fuel subsidies to the subsidized cost of the generator components, the cost of energy can drop as low as $ 0.138/kWh as shown in figure 12. Thus alternative fuel options for the diesel generator, such as bio-diesel or heavy fuel oil can effect significant changes to the energy cost. And as observed for this case, the mini-grid energy cost attains grid parity at over 90% subsidy to the system costs.

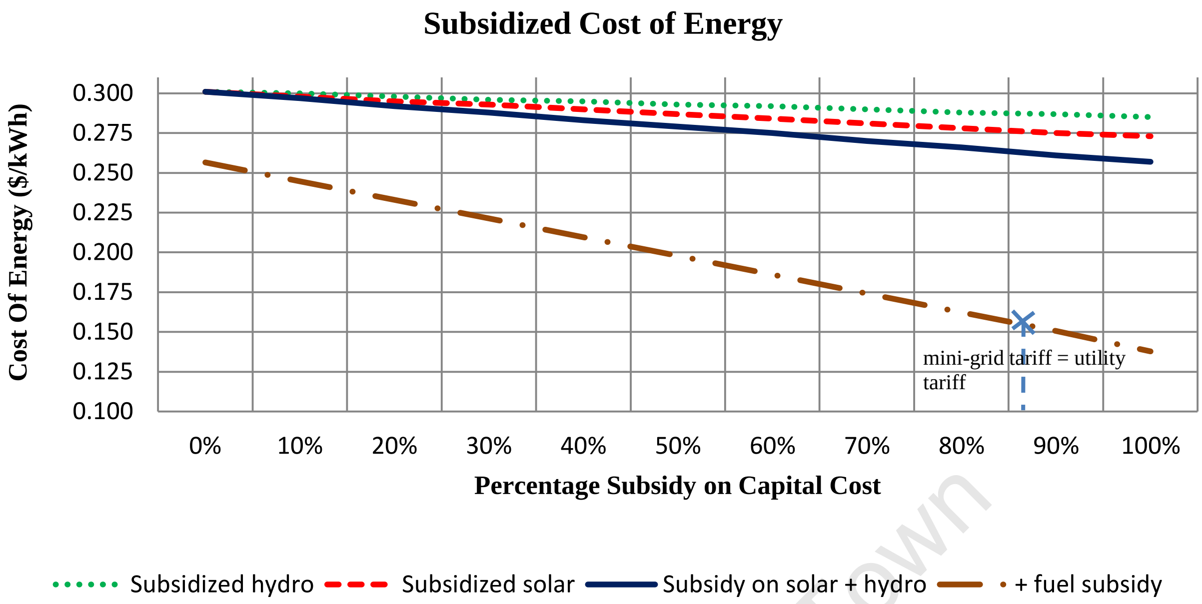


Figure 26: Effect of subsidizing the system capital costs

Also, Uganda currently relies on approximately 138MW of hydro energy, 50 MW HFO, 100MW thermal diesel and 17MW from small-hydro projects (Semitala, 2009). Uganda has vast renewable energy potential as shown by some of the estimates in table 3.

In addition to providing a potentially clean energy economy, these renewable resources are a potential tool for generating carbon credits.

Table 3: Renewable resource potential in Uganda (MEMD, 2007)

Energy Source	Estimated electrical potential (MW)
Hydro	2,000
Mini-hydro	200
Solar	200
Biomass	1,650
Geothermal	450

The formula for calculating carbon credits = (renewable energy generation) × EC × emission factor × \$/tonne of CO_2 × Hours of generation in a year at a given PLF (A. M. Jain, 2007)……………………………………………………………………………….. **(3)**

Where; EC is the CO_2 emission coefficient for diesel power generators = 0.8 (IPCC, 2006),

Emission factor = Carbon per kg of diesel fuel used to produce energy × (44/12) = 74.1kg CO2/GJ = 0.3tonne CO_2/MWh (IPCC, 2006)

At a cost of carbon = \$ 3/ tonne of carbon (A. M. Jain, 2007), and a Plant Load Factor (PLF) assumed at 70% for diesel generators, the carbon credit potential from replacing the thermal generation with renewable energy generation from the solar resources in Uganda can be approximated through equation 3 as:

= 200MW × 0.8 × 0.3tonne of CO_2/MWh × 3 \$/tonne of $CO_{2.}$ × (8760 × 70%) hrs/year

= 200 × 0.8 × 0.3 × 3 × 6132 = \$ 883,008/yr

If utilized, carbon credits offer another option of potentially offsetting the energy cost in renewable energy mini-grids. And Uganda's vast renewable energy resources can benefit the countries rural electrification desires, while also generating income through these projects.

4.4.9 System comparison with the utility grid extension

Decisions for implementing a mini-grid system in rural areas are often made based on a comparative basis with the cost of extending the electricity grid. There is often a cut-off distance at which implementing a mini-grid is a more viable solution than grid extension. Using the designed hybrid mini-grid system for Wanale, in the absence of reliable information on the cost of grid extension in Uganda, cost values for grid extension comparison are taken from (Rolland Simon & Guido Glanio, 2011) as shown in table 5. Inputs in HOMER software include; Uganda's current residential electricity tariff of

Ush.385/kWh (Kasita, 2010), at an exchange rate of 1:2500 USD to Ush = \$0.154/kWh, grid operation and maintenance costs of \$ 180/yr/km (K. Kusakana, 2009).

Table 4: Cost of grid extension (source: (Rolland Simon & Guido Glanio, 2011))

Country	Labor & other costs	Materials	Total ($/km)
Kenya	$ 6,590	$ 5,960	12,550
Senegal	$ 5,150	$10,810	15,960
Mali	$ 2,590	$15,170	19,070

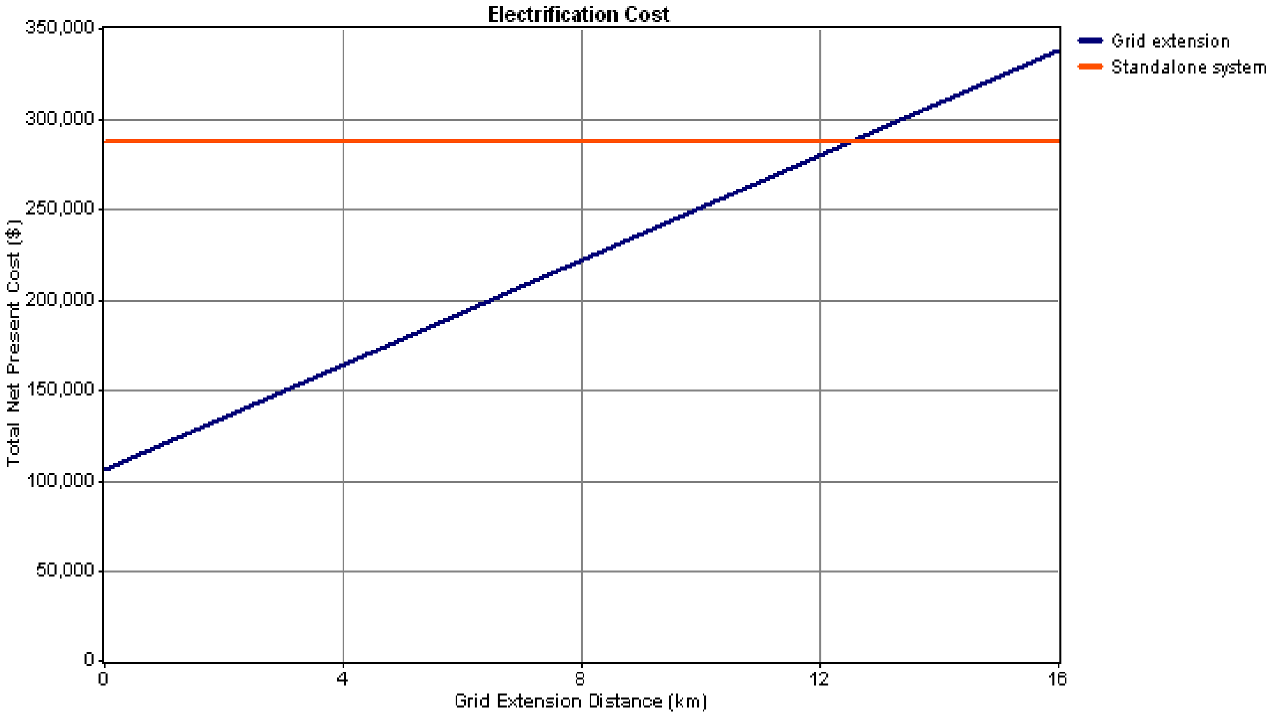


Figure 27: Grid extension break-even distance at grid extension cost of \$ 12,550

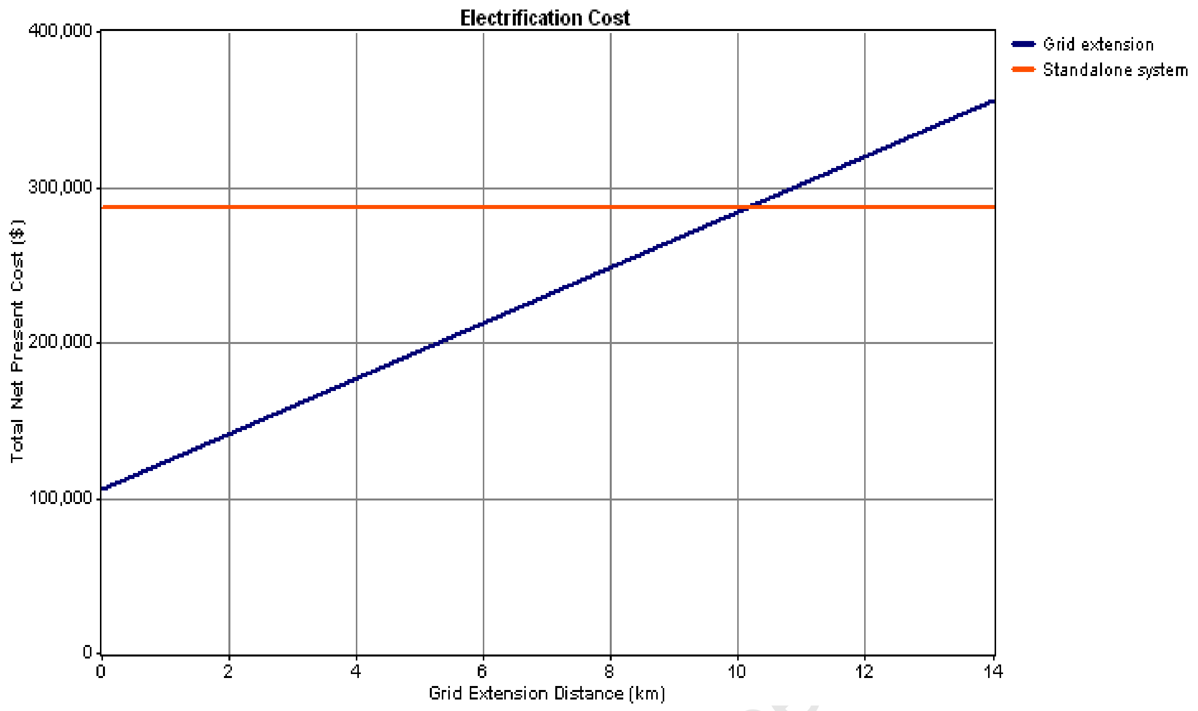


Figure 28: Grid extension break-even distance at grid extension cost of $15,960

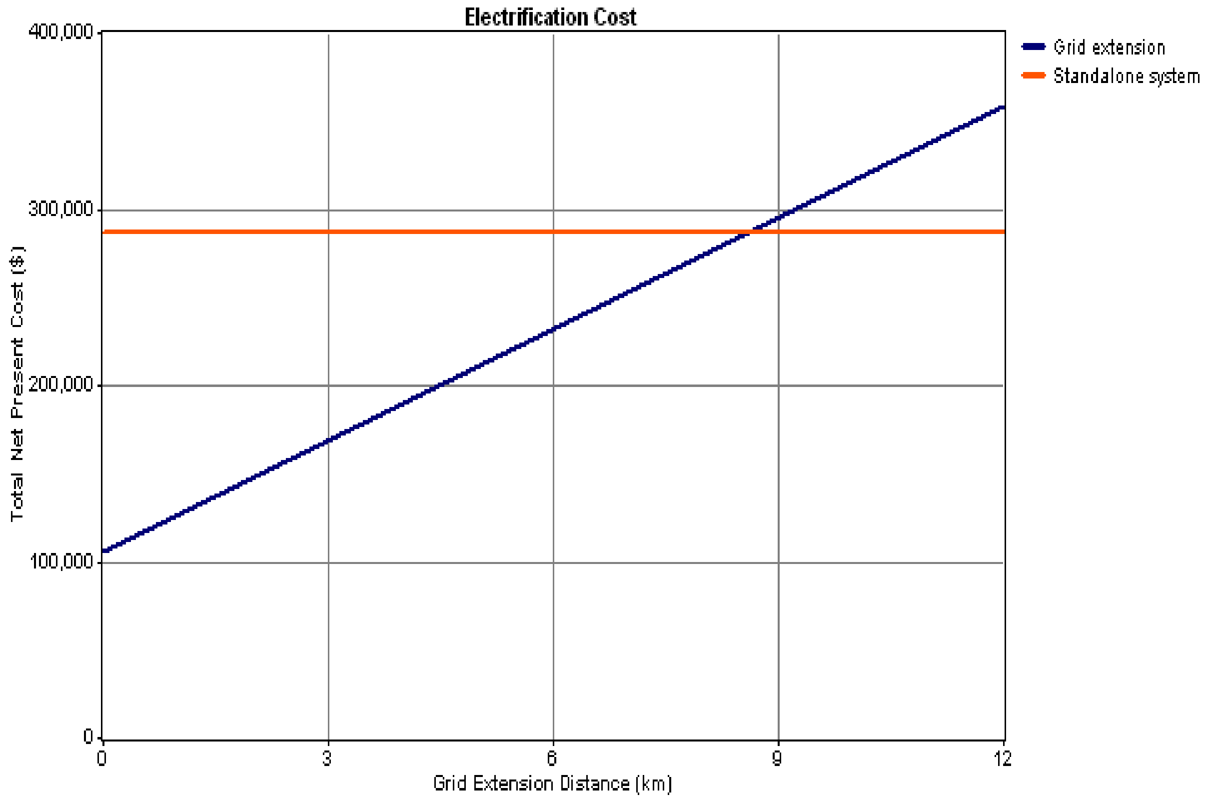


Figure 29: Grid extension break-even distance at grid extension cost of $ 19,070

It is observed that the grid-extension break-even distances for the scenarios in figures 26-28 are 12.5, 10.1, and 8.61km respectively. Given that the nearest grid electricity distribution line is 7km away from Wanale village, for all the simulated distances, grid extension offers a cheaper electrification scenario for the village. However, there are other issues to take into consideration that may impede the option of grid-extension and thus favor the option of distributed generation (Ezor, et al., 2009); some of these may include:

- The difficulties on the terrain between the grid access point and the community, such as mountains steep valleys, or marshes, which can make line extension very difficult. Wanale's location below the foot of a mountain giving it a steep terrain, adds extra difficulty to the option of grid extension;
- Also, for the case of Uganda's poor transmission infrastructure, consideration has to be made for additional transmission losses incurred by costly grid-extension to a rural area, while a mini-grid eliminates those costs;
- There're also issues of theft of transmission apparatus, especially for transmission and distribution lines covering longer distances;
- Furthermore, in a country like Uganda where generation capacity is inadequate to meet the national electricity demand, load-shedding becomes a necessity to balance the demand with supply. Energy utilities often target small unreliable customers for load shedding, thus rural consumers will have their power supply interrupted more frequently than most urban areas.

Therefore, although the option for extending the electricity grid to the village is viable, but given the topography of the area, the probability of the energy utility considering it becomes slim. Also, extending the electricity grid would not necessarily guarantee reliable energy supply to the people of Wanale, as the hybrid mini-grid system would.

So in the event that the grid is finally extended to the village, an operational scenario in which the mini-grid is interconnected with the utility grid is presented in chapter 5.1. Also, a variable pricing model is discussed that can enable energy affordability.

4.5 The Impact of Energy Storage on Hybrid Mini-grid System Operation

Customers expect electricity supply which is available all the time, is free from impromptu interruptions and provides for the safe operation of all their appliances. The fact that consumers have the freedom to alter their demand at any time, and given the inability to store AC power, creates this underlying power systems control task; with the greatest difficulties posed by those periods during the day in which the rates of load changes are fastest. Present methods used by utilities to handle this uncertainty require redundancy of system equipment and/ the operation of additional generation to cater for demand fluctuations and for peak consumption. With power systems currently being constrained by fuel economics and the community’s environmental expectations, running diesel generators for extended periods is no longer a sustainable solution for meeting these daily load fluctuations (Sutanto, 2002).

In small isolated power systems utilizing renewable energy technologies configured with conventional diesel generators, in order to save fuel, diesel generators should not be operated continuously. The addition of energy storage to system operation eliminates this problem to some extent, providing a variety of operating flexibilities, which can have significant impacts on system reliability and economics. In order to use renewable energy sources as viable power generation, energy storage is incorporated in these systems in order to match the intermittent power availability with the instantaneous power demand. Thus fast responding battery energy storage, with sufficient capacity and rating, can benefit the day to day operation of the power system, by responding to fast demand variations (Billinton Roy & Bagen, 2006).

Research on energy storage and reliability has been done on a number of power systems utilizing renewable energy generators. In a study done by (Bagen & Roy Billington,

2005) on an isolated power system configure to utilize wind, PV and a diesel generator, two risk indices are used to investigate the impact of energy storage on power systems operation. The loss of load expectation (LOLE) measures how long, on average, within a specified duration, the available capacity is likely to fall short of the demand (hours/ year), while the loss of energy expectation (LOEE) is a measure of the expected energy shortage within a specified period (kWh/ year). These indices are calculated through Monte Carlo simulations to model the loads and supply configurations. This is applied to the operation of three small power systems utilizing diesel, PV and Wind in different configurations. The LOLE is simulated as a function of the energy storage capacity for the three basic system configurations, as shown in the graph in figure 29. And as observed, the addition of the energy storage device significantly lowers the LOLE of the power systems. It enhances the reliability of the small power systems, regardless of the type of energy sources installed in the system. Also, at a certain value, the benefits obtained from additional capacity of the energy storage system become minimal. This is due to the intrinsic energy limitations of the site resources.

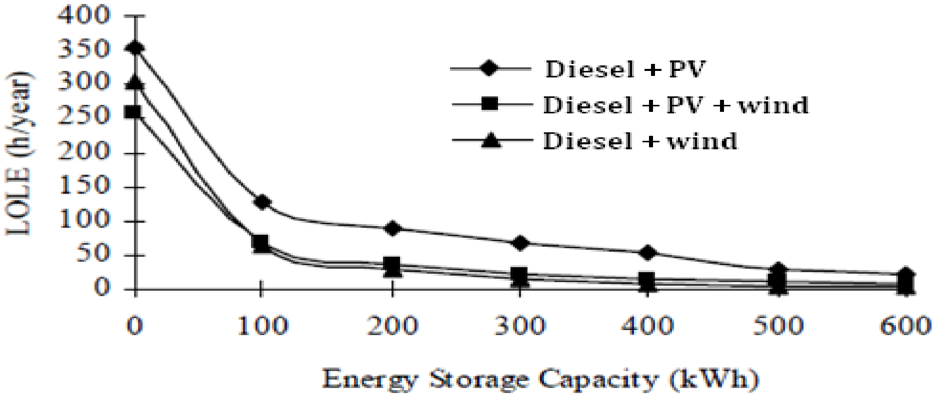


Figure 30: Effect of the Energy Storage and Capacity on the LOLE (source: (Bagen & Roy Billington, 2005:496))

In this study, HOMER’s simulation of the hourly operation of the Wanale system design is used to demonstrate the impact of the presence of energy storage on the power systems operation. Using the system modeled in case 3, system operation can be simulated for a year's supply-demand characteristics as shown in figure 30.

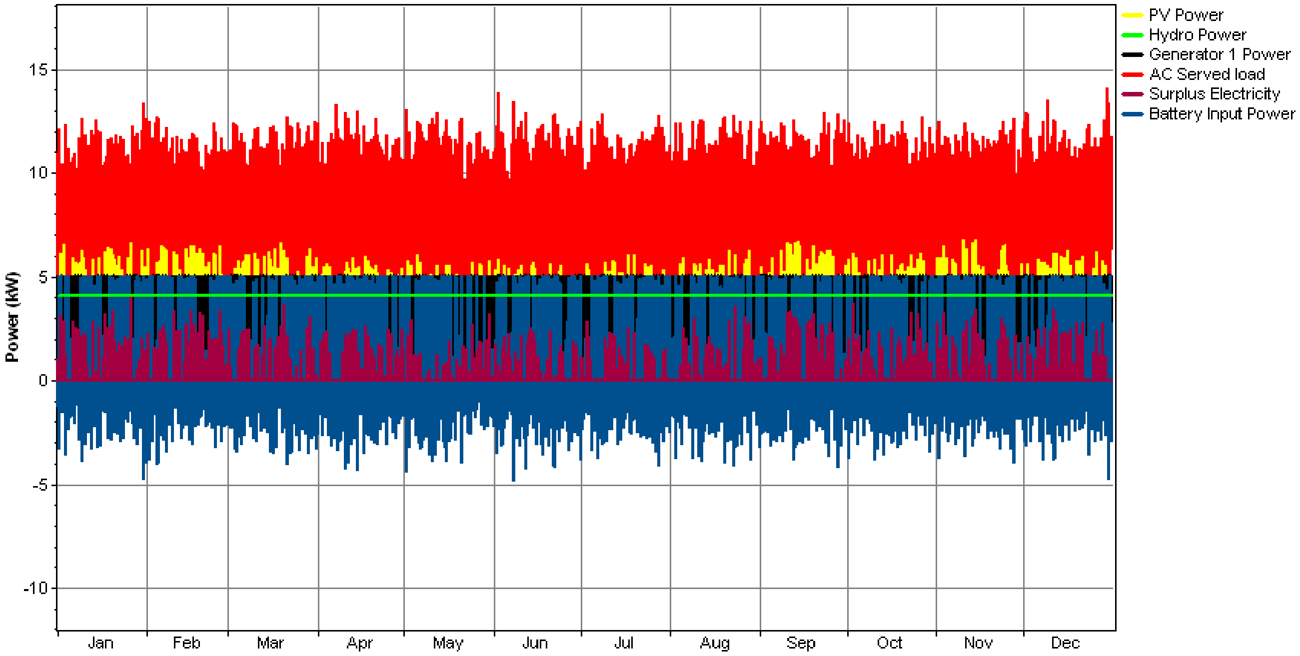


Figure 31: Annual simulation of the supply-demand characteristics for Wanale (with energy storage)

On the other hand, in the absence of energy storage, the system has to be designed with enough capacity to cater for the demand fluctuations, and at the same time be able to cater for the peak load. The hybrid mini-grid model in case 3, is simulated without battery energy storage, as shown in figure 31, (as a base study) in order to demonstrate the differences in system operation.

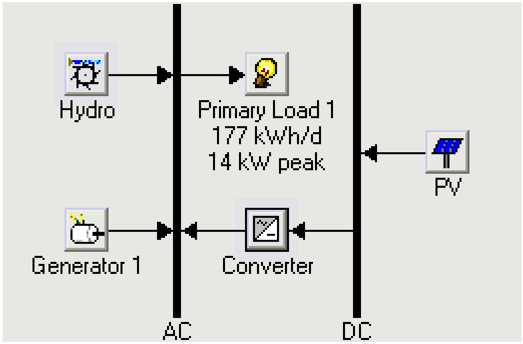
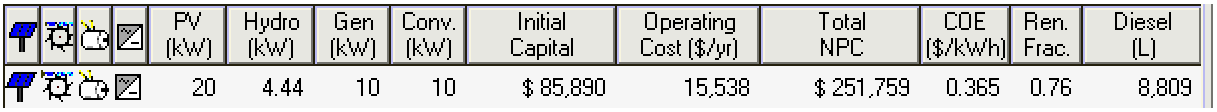
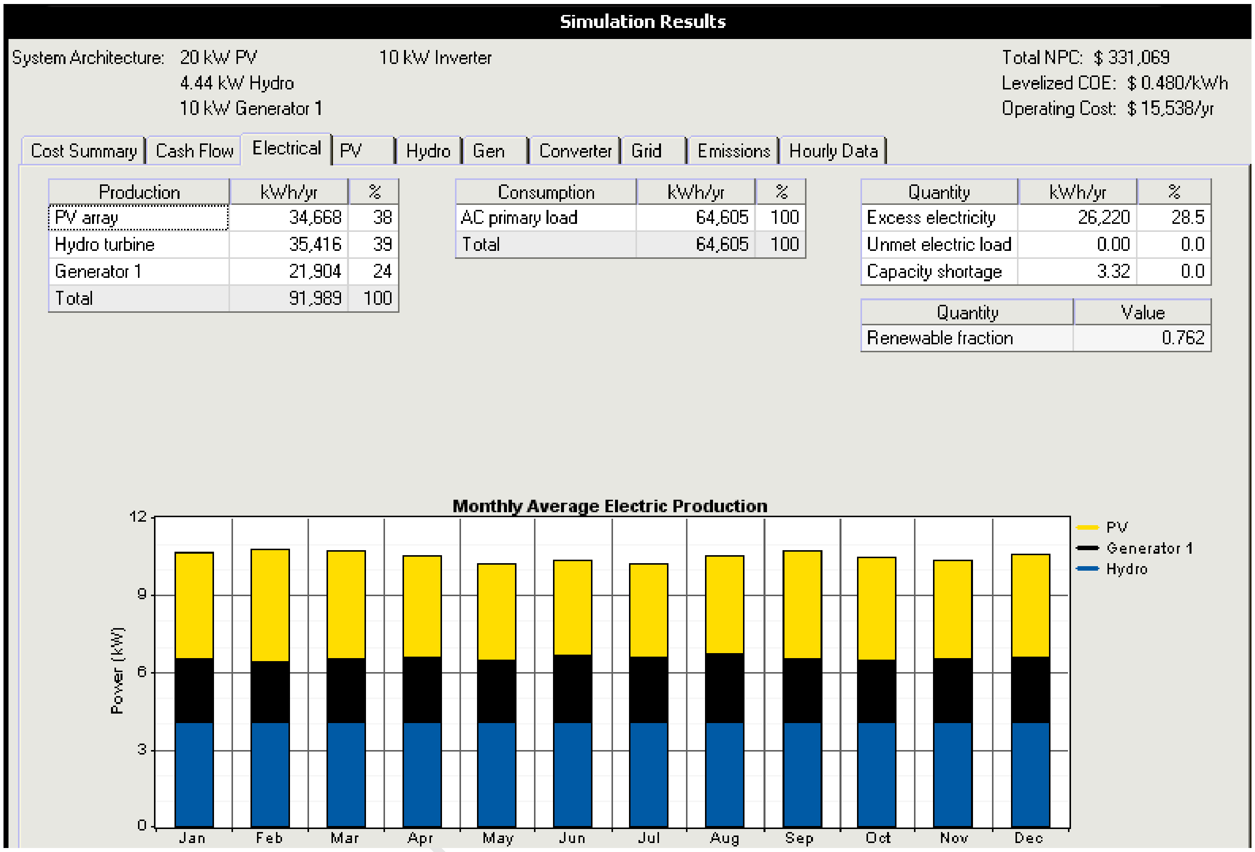


Figure 32: HOMER hybrid mini-grid configuration without energy storage



PV (kW)	Hydro (kW)	Gen (kW)	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)
20	4.44	10	10	$ 85,890	15,538	$ 251,759	0.365	0.76	8,809

Figure 33: HOMER optimization results



Simulation Results

System Architecture: 20 kW PV
4.44 kW Hydro
10 kW Generator 1
10 kW Inverter

Total NPC: $ 331,069
Levelized COE: $ 0.480/kWh
Operating Cost: $ 15,538/yr

Production	kWh/yr	%
PV array	34,668	38
Hydro turbine	35,416	39
Generator 1	21,904	24
Total	91,989	100

Consumption	kWh/yr	%
AC primary load	64,605	100
Total	64,605	100

Quantity	kWh/yr	%
Excess electricity	26,220	28.5
Unmet electric load	0.00	0.0
Capacity shortage	3.32	0.0

Quantity	Value
Renewable fraction	0.762

Figure 34: Hydro-PV-diesel system electrical supply properties

As observed in figure 32, without energy storage, the hybrid mini-grid system optimizes at a 20kW PV array, and a 10kW diesel generator, in addition to the 4.4kW base supply of hydro. And as noted in figure 33 by the amount of excess energy (28.5%), this system is oversized. The excess energy is a product of the redundancy in system operation to match the fluctuating demand. With the system simulated for a whole year or operation as shown in figure 34, a comparison can be made between the two systems (with and without energy storage) to identify some of the notable differences.

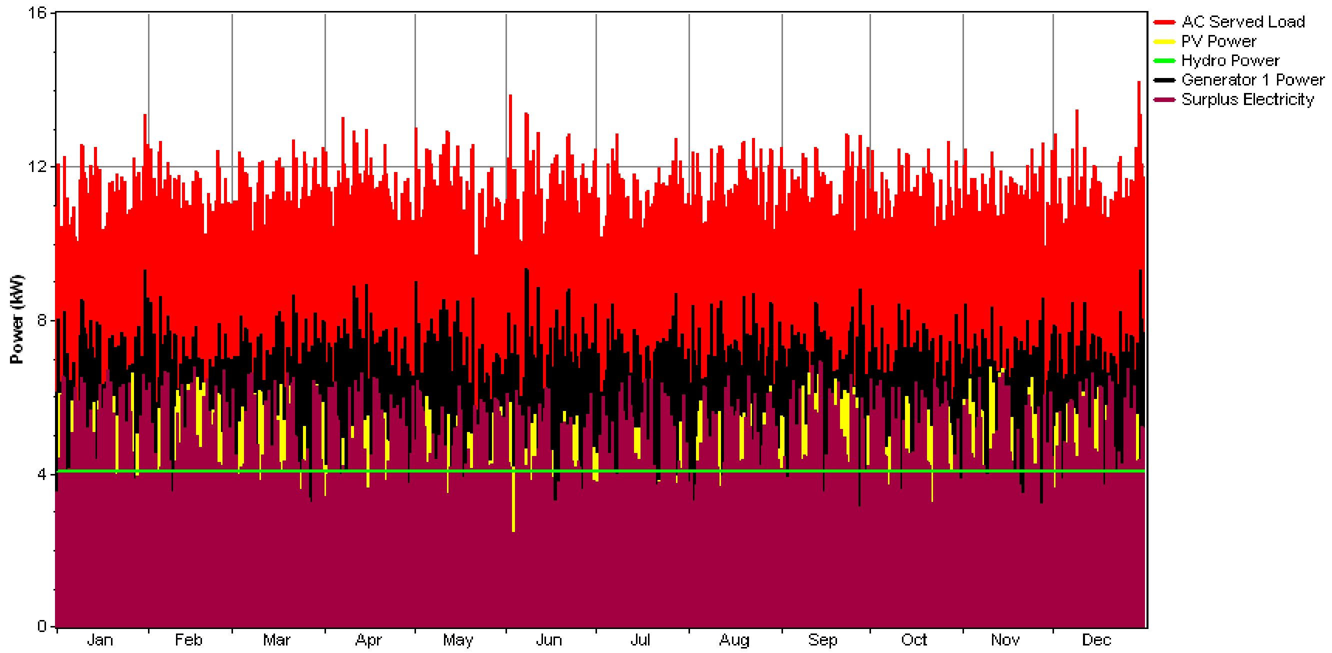


Figure 35: Annual simulation of the supply-demand characteristics for Wanale (without energy storage)

The most important aspect to note in the comparison of the two simulated systems (figures 30 and 34), is the notable difference in how much surplus energy is available in both systems throughout the year. Although in both systems, there is a surplus in the amount of available energy needed to meet the demand, the surplus amount in the system without energy storage is significantly greater. This indicates that some of the generating components in the system without energy storage are over-size. While with the presence of the energy storage facility, the electricity supply matches the demand, resulting in a significantly lower amount of surplus energy. Here, energy storage plays an important role for those periods when the demand fluctuations occur but the levels are not high enough to require an additional generator. Energy storage will also acts as a demand-side management tool allowing for storage in periods of high energy availability, thus “time shifting” the generation to meet the demand in periods of necessity (Ross, et al., 2011).

The impact of energy storage on system operation can further be quantitatively evaluated through the values table 5. And as can be observed, the inclusion of an energy storage facility in the hybrid mini-grid design offers a number of operational advantages, including:

- With energy storage, a smaller size of the diesel generator is sufficient, which operates at a better capacity factor, will make fewer starts/year, and is thus more efficient in operation;
- Another interesting observation is that, although the diesel generator in the system without energy storage operates for fewer hours a year, it uses more fuel compared to the other system. This is mainly because of the generator size, and also given that it operates even for periods of low demand, generator operation at low capacity leads to efficiency losses in fuel consumption (Ross, et al., 2011);
- Also, with energy storage in the system there're savings on fuel, and the associated fuel and maintenance costs, and given the reduced operation of the generator, the carbon dioxide emissions are also significantly reduced;
- With the presence of energy storage, a smaller size PV supply is required, thus saving on the capital costs, also the excess energy generated by the PV array is stored, while in the absence of energy storage, a larger PV supply is required, in the process producing a lot more energy than is required at particular times;
- Also, because of the need for a larger PV supply without energy storage, there is a significant addition to the capital cost of the system, which does not translate to life cycle cost savings;
- Thus the hybrid mini-grid system designed with energy storage will operate more efficiently in matching the resources to the demand, and will thus have lower operating costs and life cycle costs, resulting in a lower energy cost.

Table 5: Impact of energy storage on the dynamics of a hybrid mini-grid system

		Storage	**no storage**	**Savings**
		Value		
PV	Size (kWp)	7	20	
Generator	Size (kW)	5	10	
	Number of generator starts/yr	674	745	
	Hours of operation (hr/yr)	4,989	4,166	
	Capacity factor (%)	50	25	
	Fuel consumption (l/yr)	7,470	8,809	**- 1,339**
	Mean electrical efficiency (%)	30	25.3	
System	Surplus electricity (kWh/yr)	1,674	26,220	
	Surplus electricity (%)	2.41	28.5	
	Carbon dioxide emissions (kg/yr)	19,672	23,196	**- 3,524**
Economics	Initial capital cost ($)	51,979	85,890	**- 33,911**
	Operating cost ($/yr)	14,586	15,538	**- 952**
	Total NPC ($)	207,685	251,759	**- 44,074**
	LCOE ($/kWh)	0.416	0.480	

In conclusion, the inclusion of an energy storage facility in a hybrid mini-grid system design, not only leads to savings on the capital, operational and maintenance costs, but also significantly improves system operation, making it more efficient and reliable.

5. FUTURE CONSIDERATIONS IN THE HYBRID MINI-GRID SYSTEM DESIGN AND OPERATION

5.1 Smart Thinking: The Concept of Dynamic Pricing

Customers demand higher energy quality, reliability and affordable energy services. The concept of smart thinking, involves, among others, innovation in more optimal ways of supplying power, and employing a tariff system that promotes fairness and takes into consideration consumers that utilize peak generation, thus extending energy charges to those that use energy during peak hours. The key costs for any system are the capital and installation costs, and the running or operation and maintenance costs (O&M). Many utilities around the world employ variable pricing schemes for grid consumers; these include the time-of-use tariffs and the real-time-pricing schemes. These are mostly designed to include a demand charge to consumers who utilize peak generators (which are mostly fossil fuel based) (Zeng, et al., 2008). Rural consumers are the type of customers that try to minimize their cost function of electricity consumption as much as possible, and thus will always be on the look out for ways to save money. Variable pricing schemes eliminate the unfair system of charging an average flat-rate tariff to all consumers regardless of their consumption behavior. Traditional tariff setting in mini-grids involves the energy utility calculating the cost of energy based on the life cycle costs of the system (calculated from the capital, operation and maintenance, and the fuel costs). These are used by the utilities to calculate a flat-rate electricity charge which makes the revenues equal to the expenses plus a profit margin. For systems utilizing multiple generation technologies, these flat-rate tariffs do not reflect the true and time-varying costs of electricity supply during the actual time of consumption (Ulbig, et al., 2010).

Hybrid mini-grid systems comprise a number of generation technologies, utilizing different resources to supply electricity. These different technologies will generate electricity based on the availability of resources and also the level of demand. Thus at anyone time during operation, different configurations of the supply technologies will be generating electricity at different times of the day. Taking the simulated operation of the proposed hybrid mini-grid system for Wanale, this can be illustrated as shown in figure 35.

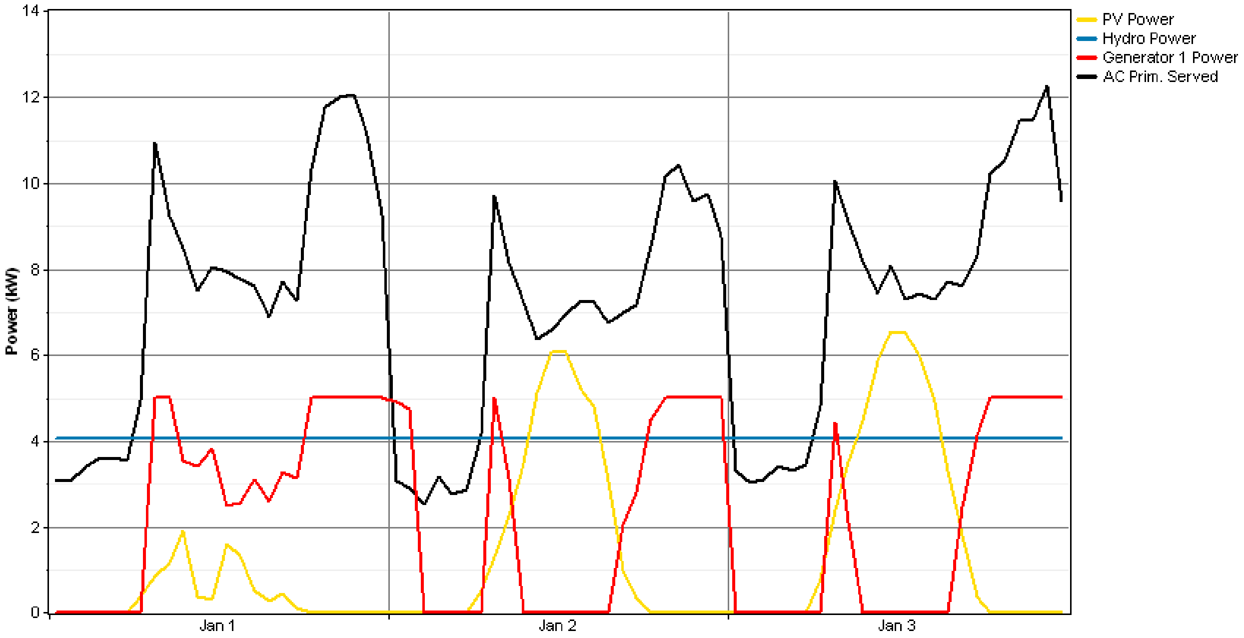


Figure 36: Three day supply-demand situation

And as observed, for a demand-supply situation simulated for three days of January, there is an hourly variability to the supply situation. With hydro providing the base-load electricity supply, for periods of low demand, the other generators are offline. And during the day when the solar is available, it contributes to the supply, and when the level of demand calls for it, the diesel generator is dispatched to provide the additional supply. This cycle of operation is not reflected in a flat-rate electricity charge. The levelized energy cost of a generation system is calculated based on the fixed and variable costs of the components. The renewable energy generators and the battery contribute a fixed charge to the energy cost, while the diesel generator contributes both a fixed, and a variable cost due to its fuel consumption, with the fuel charges forming the biggest contribution to the life cycle costs of the system (Michel, et al., 2010). The idea is to isolate the fixed from the variable charges of the system, thereby varying the energy cost to reflect consumption periods of high demand in which the diesel generator is required.

Given that the diesel generator is employed in the system as a form of backup, its cost influence to the system should also reflect this situation, such that its operation translates to an additional cost to the base energy price.

In order to achieve higher system sustainability in hybrid power systems, the EU funded a project called “Mini-Grid Kit”, with the objective of providing innovative research solutions concerning energy and demand management system (Michel, et al., 2010). One of the aims of this project was to design a dynamic energy management system, with a pricing module capable of calculating a real-time energy price depending on the actual state of system operation. The pricing module would be able to calculate an energy price based on the system fixed and variable costs, whereby the fixed costs are used to calculate the costs per day and with the load forecast the costs per kWh as a base price level. And when the diesel generator has to be operated for additional supply, the variable price per kWh is added to the base price. This results in the total energy price that is charged from the consumer. The advantage to be offered by this scheme would be the ability to give consumers the motivation to consume energy at low prices when no auxiliary generation from the diesel generator is required (Michel, et al., 2010).

Using HOMER software to illustrate this concept, the system that is proposed for Wanale is simulated to exclude the diesel generator as shown in figure 36 below. This is achieved by adding a capacity shortage to the system to signify the percentage energy deficit in the absence of the diesel generator’s contribution. And as observed in figure 37, at a capacity shortage of 39%, the energy cost = $0.312/kWh.

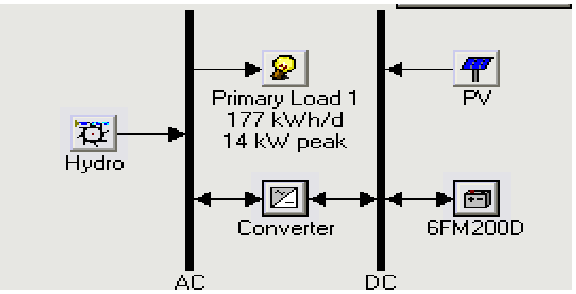


Figure 37: System design in HOMER

PV (kW)	Hydro (kW)	6FM200D	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
7	4.44	15	5	$ 129,289	2,024	$ 150,899	0.312	1.00	0.39

Figure 38: HOMER optimized results

And as observed in the simulations in figure 35, the generator will not be operational throughout the day, acting as additional supply when the demand calls for it. Thus the energy cost will vary between the periods when all the components are contributing to the supply, and the periods when the diesel generator is offline, and as observed, this occurs for at least twice a day through out the month. For this study, the simulated energy cost will thus vary between \$0.416/kWh and \$0.312/kWh. By averaging this cost of energy a price responsive consumer, through demand-side management could pay approximately \$0.364/kWh instead of the flat-charge of \$0.416/kWh, thus having the opportunity to save some money.

5.2 Hybrid Mini-grid System Incorporating a Fuel Cell

Fuel cells are electrochemical devices, sometimes comparable in operation to conventional batteries, which convert the chemical energy of fuel directly into DC electrical energy (HYRESS, 2008). The modularity and portability of fuel cells gives them a wide range of potential application, including in distributed generation systems (mini-grids). Among the different types, the most popular low temperature fuel cell is the Proton-Exchange Membrane Fuel Cell (PEMFC) shown in figure 38. The basic physical structure of a fuel cell consists of two porous electrodes (anode and cathode) and an electrolyte layer in the middle (membrane).

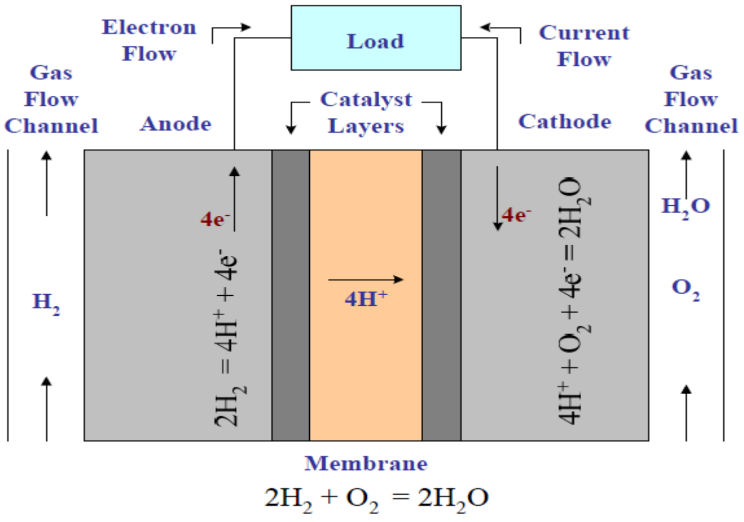


Figure 39: Schematic diagram of a PEMFC (source: (Caisheng Wang, 2006))

The electrolyte layer is a good conductor for ions (positive or negative charged), but not for electrons. The electrolyte can either be solid or liquid; a PEMFC has a solid electrolyte. The type and chemical properties of the electrolyte used in fuel cells are very important to their operating characteristics, such as their operating temperatures. Fuel cell operation is powered by the flow of a fuel gas such as hydrogen, which could be pure or derived from natural gas, fossil fuels, or even water, while the oxidant is usually oxygen or air. Fuel is fed continuously to the anode and oxidant is fed continuously to the cathode. Where the anode is the electrode from which electrons leave (negative) and cathode is the electrode to which the electrons go (positive). The electrochemical reactions take place at the electrodes to convert the chemical energy into electricity (Caisheng Wang, 2006).

The application of fuel cell technology in hybrid mini-grid systems presents an option to replace the diesel generator with a fuel cell system. Connecting a fuel cell to such a system requires either a customized DC-DC-converter for direct connection with the battery bank, or a separate inverter for DC-AC conversion which then connects to the AC bus (HYRESS, 2008).

Some of the advantages offered by fuel cell technology (PEMFC) include:

- Higher conversion efficiencies (up to 50%) as compared to diesel generators;
- PEFCs typically operate at low temperatures (60 to 80^{O}C), allowing for potentially faster startup;
- Fuel cell operation is free from noise and environmental pollution;
- Also, due to much lower maintenance cost, in the future, fuel cells are expected to generate electricity at lower cost than conventional diesel generators even at higher initial investment cost.

A number of studies have been done on fuel cell application in hybrid mini-grid system designs, including (Alam Mohammad Saad & Gao David W, 2007) & (Mirazimi Seyed Javad & Fathi Mohammad, 2011).

A configuration of a PV/Wind/Fuel cell/Battery system is simulated by (Rohani, et al., 2010) in HOMER for application in the electrification of a remote village. With the main power coming from the wind and PV generators, the battery and fuel cell are utilized as backup. The model design is as shown in figure 39.

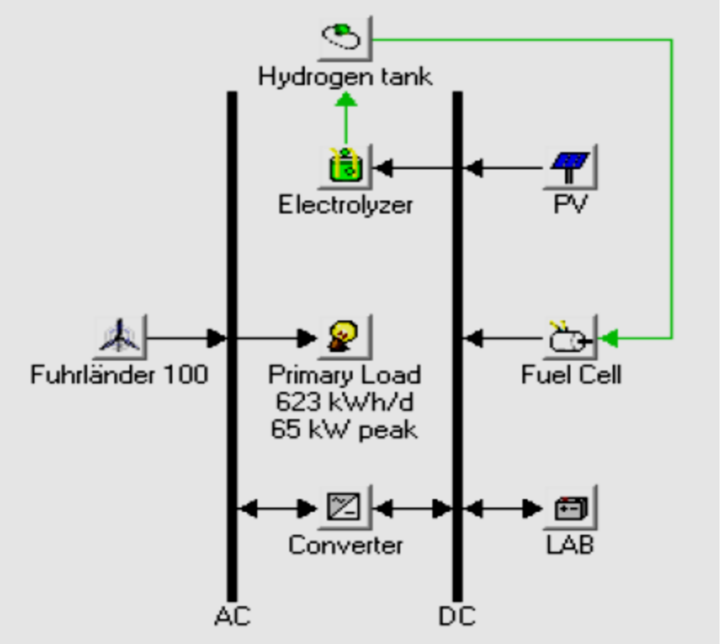


Figure 40: Proposed PV/Wind/Fuel cell/Battery model hybrid mini-grid design (source: (Rohani, et al., 2010)).

The simulation results indicate that the proposed hybrid system would be a feasible solution for distributed generation of electric power for off-grid applications at remote locations.

5.3 Effect of extending the electricity grid on the life of the mini-grid system

Mini-grid systems in many countries are phased out of operation when the utility grid is extended to the area. Thus one of the criteria to implementing a mini-grid system in an area should be the lack of electrification prospects for the foreseeable future (NRECA, 2000). But priorities change, and unanticipated circumstances may lead to the extension of the utility grid to the area. This may be due to political promises, or investor prospects. Therefore modern mini-grid system designs should be able to adapt to the changes in operating conditions (Rolland Simon & Guido Glanio, 2011).

One option of dealing with grid extension is to interconnect the mini-grid to the utility grid, finding an optimal operating strategy, and phasing out the individual min-grid components as their lifetimes expire. Hybrid power supply systems incorporating renewable energies have a complex structure due to the fluctuations in the raw resources (wind or solar), resulting in the need for power conditioning units in the form of converters. One of the most important aspects of hybrid mini-grid systems is the ease with which they can be expanded with additional generators and/or connected to other grids (HYRESS, 2008:12). This is achieved through the application of specialized components for voltage and frequency control. For a detailed look at the power systems involved in mini-grid connection to the grid and the challenges that need to be overcome to ensure optimum operation of grid-connected mini-grids, refer to (Shang W T & Redfern M A, 2011).

For the hybrid mini-grid system designed at Wanale, for a scenario in which the utility grid is extended to connect the village, a proposed approach would be;

Firstly, for the diesel generator to be immediately phased out from the mini-grid system given that its lifecycle costs constitute the highest operational and fuel costs. The grid can be interconnected with the mini-grid to take over the supply that was provided by the diesel. The system design model will thus take on the form shown in the figure 40.

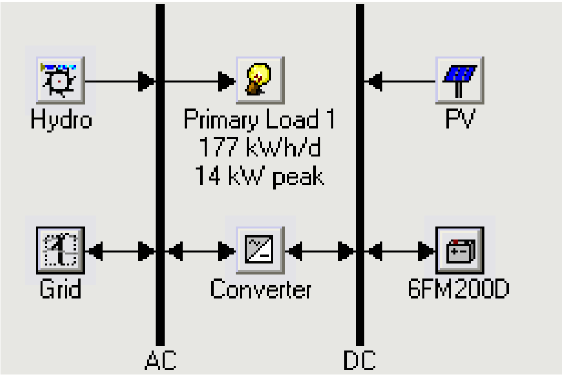
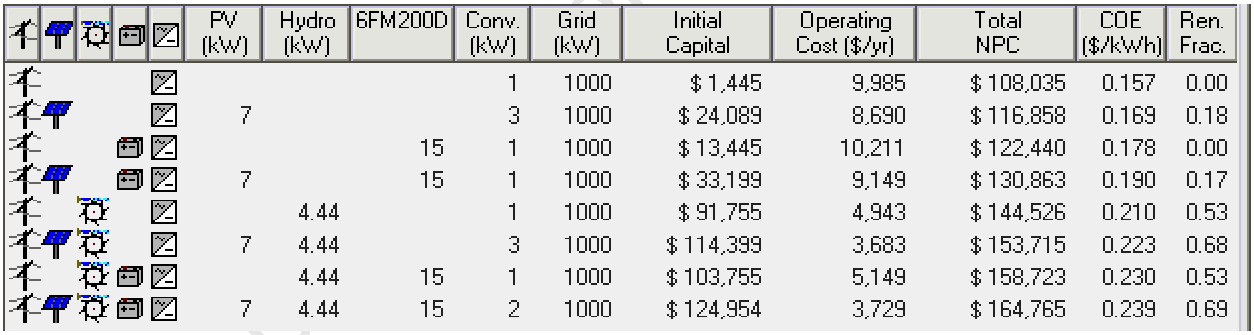


Figure 41: HOMER system design

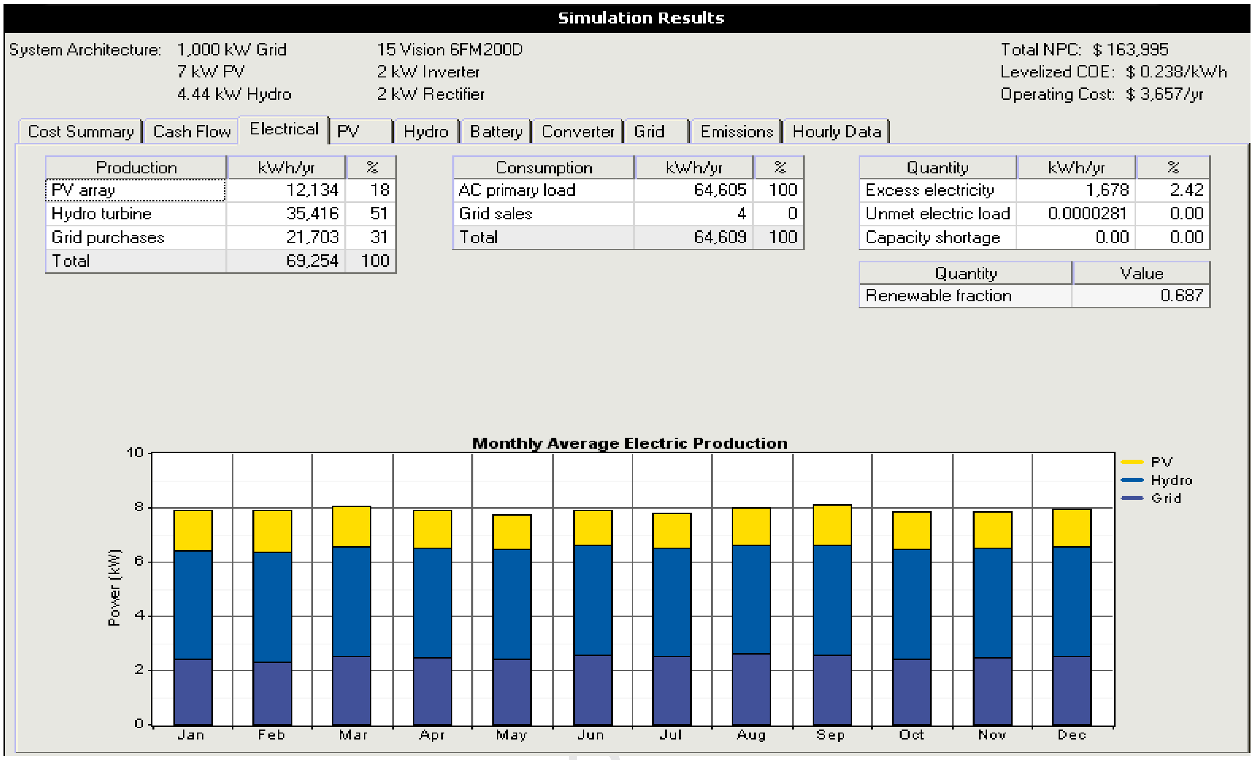
At a grid electricity price of $ 0.154/kWh, the optimization options for the system are as shown in the figure 41. It should be noted that the grid extension costs do not contribute to the energy cost entered in HOMER. It is assumed that with grid extension, the members of the village will be charged the residential grid tariff.



					PV (kW)	Hydro (kW)	6FM200D	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
✓				✓				1	1000	$ 1,445	9,985	$ 108,035	0.157	0.00
✓	✓			✓	7			3	1000	$ 24,089	8,690	$ 116,858	0.169	0.18
✓			✓	✓			15	1	1000	$ 13,445	10,211	$ 122,440	0.178	0.00
✓	✓		✓	✓	7		15	1	1000	$ 33,199	9,149	$ 130,863	0.190	0.17
✓		✓		✓		4.44		1	1000	$ 91,755	4,943	$ 144,526	0.210	0.53
✓	✓	✓		✓	7	4.44		3	1000	$ 114,399	3,683	$ 153,715	0.223	0.68
✓		✓	✓	✓		4.44	15	1	1000	$ 103,755	5,149	$ 158,723	0.230	0.53
✓	✓	✓	✓	✓	7	4.44	15	2	1000	$ 124,954	3,729	$ 164,765	0.239	0.69

Figure 42: HOMER optimization

As observed a number of configuration options exist for such a system, with the cheapest having PV providing additional supply to the grid electricity when necessary. But disregarding the option of the immediate riddance of the hybrid mini-grid system components, and assuming a scenario in which at the point of grid connection, all the original system components are still actively contributing to the village supply. With the grid interconnected with the mini-grid, for a supply situation in which the utility grid, hydro, solar and energy storage contribute to the village electricity supply situation, the simulated system electricity supply properties will be as shown in figure 42:



System Architecture: 1,000 kW Grid
7 kW PV
4.44 kW Hydro
15 Vision 6FM200D
2 kW Inverter
2 kW Rectifier

Total NPC: $ 163,995
Levelized COE: $ 0.238/kWh
Operating Cost: $ 3,657/yr

Production	kWh/yr	%
PV array	12,134	18
Hydro turbine	35,416	51
Grid purchases	21,703	31
Total	69,254	100

Consumption	kWh/yr	%
AC primary load	64,605	100
Grid sales	4	0
Total	64,609	100

Quantity	kWh/yr	%
Excess electricity	1,678	2.42
Unmet electric load	0.0000281	0.00
Capacity shortage	0.00	0.00

Quantity	Value
Renewable fraction	0.687

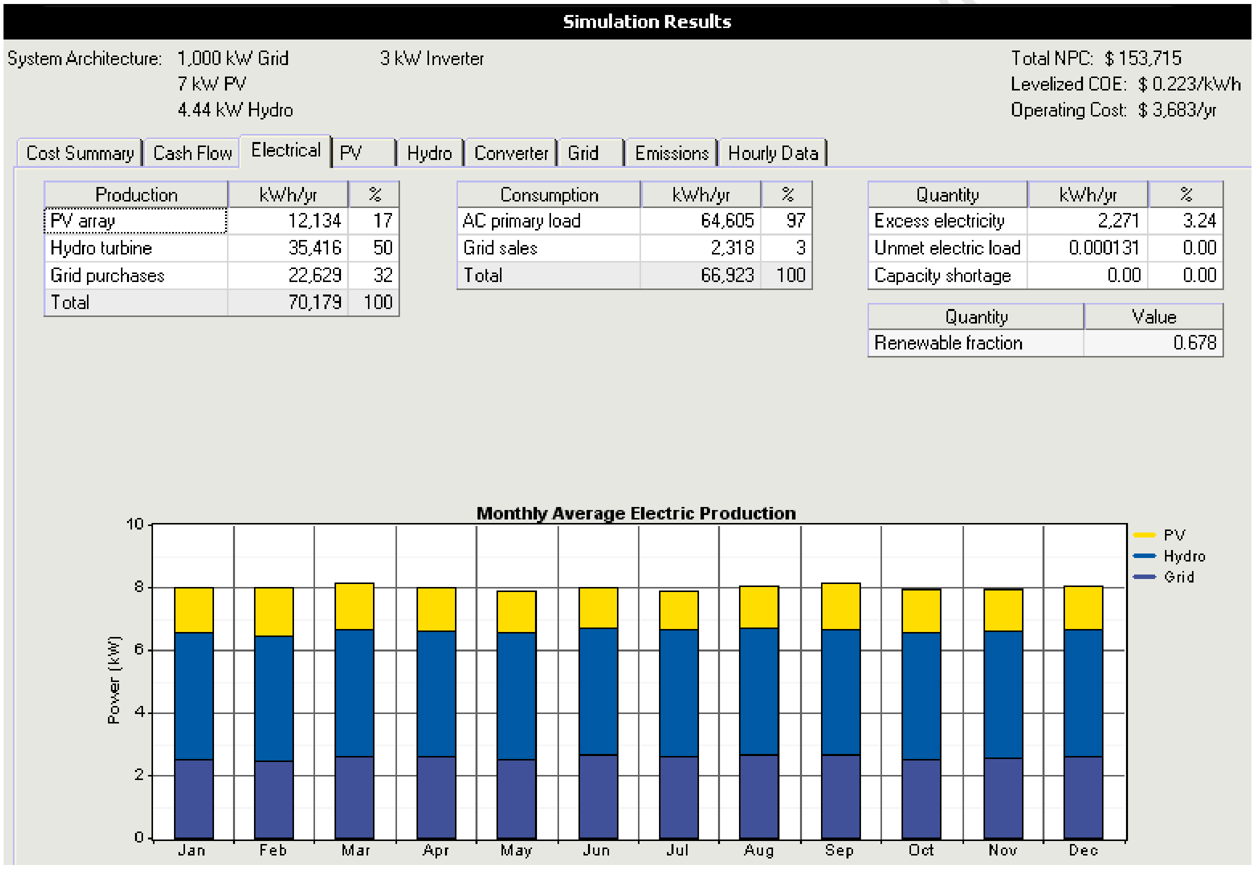
Figure 43: Grid-hydro-PV-battery electrical supply properties

And as observed, the grid will contribute to 31% of the electricity supply annually, resulting in a system levelized energy cost of $0.238/kWh. This system provides a slightly higher energy cost than the electricity grid, but it also provides a number of operational advantages such as;

- For a country such as Uganda, where energy utilities load-shed to balance the demand with supply, this system offers power supply reliability, given that in the absence of grid supply, there're additional supply options to cater to the village demand.
- Another advantage to this system would come in the form of a smart system, where the excess energy from the mini-grid can be sold to the grid, thus generating

some income for the village, which can then be used to further offset the electricity tariffs.

This system remains configured in this mode until such a point when the component's lifetimes expire. The batteries will be the first to go, replacing them will not be necessary as the system will operate fine without them as shown in figure 43. The only bug will be the excess energy from the PV array, but this can be sold to the utility grid if the provision is available. And as observed this system provide for a lower overall energy cost.



System Architecture: 1,000 kW Grid 3 kW Inverter
7 kW PV
4.44 kW Hydro

Total NPC: $ 153,715
Levelized COE: $ 0.223/kWh
Operating Cost: $ 3,683/yr

Production	kWh/yr	%
PV array	12,134	17
Hydro turbine	35,416	50
Grid purchases	22,629	32
Total	70,179	100

Consumption	kWh/yr	%
AC primary load	64,605	97
Grid sales	2,318	3
Total	66,923	100

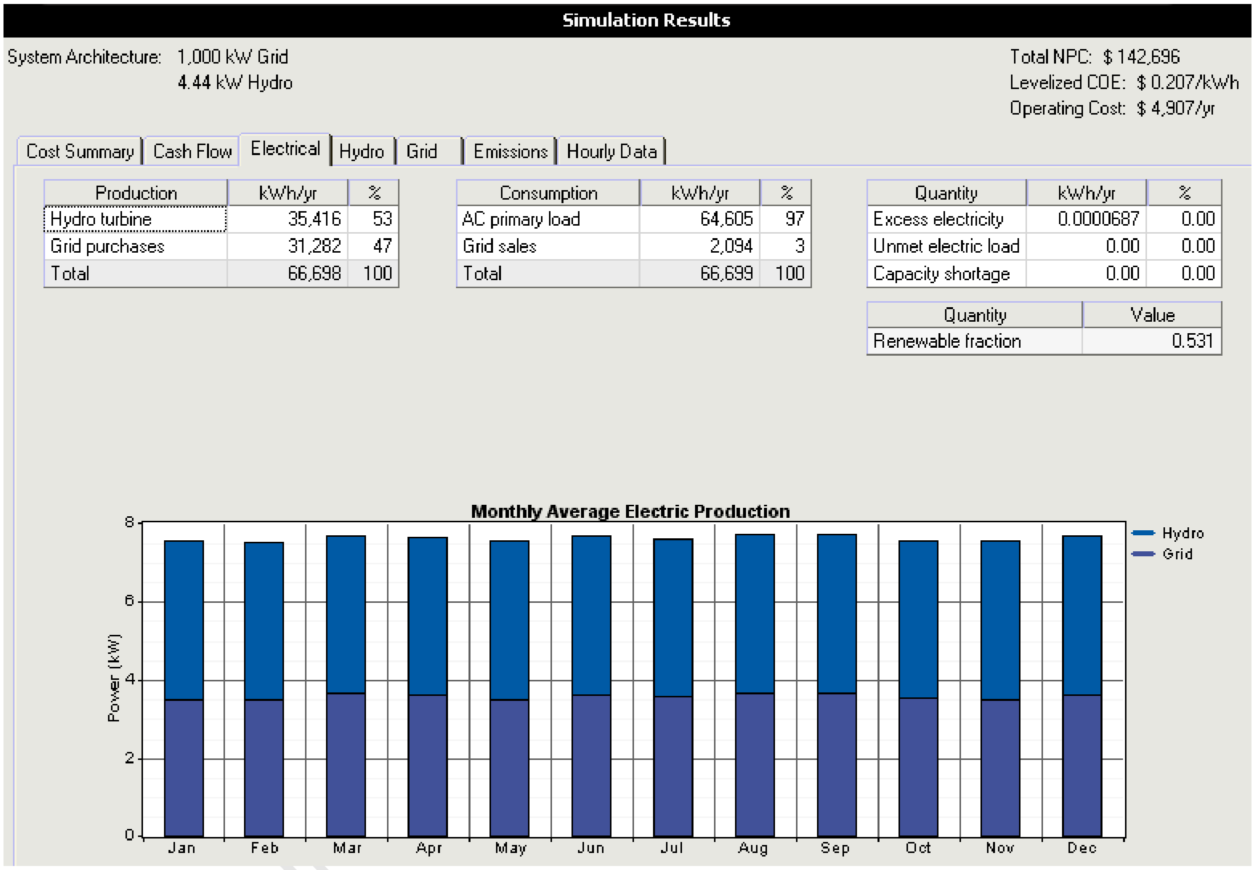
Quantity	kWh/yr	%
Excess electricity	2,271	3.24
Unmet electric load	0.000131	0.00
Capacity shortage	0.00	0.00

Quantity	Value
Renewable fraction	0.678

Figure 44: Grid-hydro-PV electrical supply properties

At a point in the future, the PV arrays will also be phased out of supply, leaving the Pico-hydro plant interconnected with the grid supply. This system will operate optimally, at a further reduced energy cost of $ 0.207/kWh as shown in the supply properties in figure 44. Given that hydro electricity structures are designed for life times of over 30 years, the

Pico-hydro plant can provide operational support to the grid supply; while still retaining the option of selling back the excess electricity to the grid. It should be noted that, at this point a safe assumption can be made that the village consumption would have grown exponentially to include heavier loads to the system. Thus grid connectivity would come as a welcome addition the supply system.



System Architecture: 1,000 kW Grid
4.44 kW Hydro

Total NPC: $ 142,696
Levelized COE: $ 0.207/kWh
Operating Cost: $ 4,907/yr

Production	kWh/yr	%
Hydro turbine	35,416	53
Grid purchases	31,282	47
Total	66,698	100

Consumption	kWh/yr	%
AC primary load	64,605	97
Grid sales	2,094	3
Total	66,699	100

Quantity	kWh/yr	%
Excess electricity	0.0000687	0.00
Unmet electric load	0.00	0.00
Capacity shortage	0.00	0.00

Quantity	Value
Renewable fraction	0.531

Figure 45: Grid-hydro electrical supply properties

5.3.1 Dynamic pricing model for the system

The grid interconnected system also offers the opportunity for implementing a form of dynamic pricing scheme, either as a time-of-use tariff or real-time pricing, to reflect the different supply variations during the day. In this scheme, the energy cost varies to reflect periods of the day when the grid does or does not contribute to the electricity supply situation as shown in figure 45. And as observed in the figure, grid supply is not constant throughout the day and thus through out the week. For the periods of the day when the solar energy is available, its energy contribution is given priority, with the grid providing the additional supply if necessary. When the demand is also low enough to be met by the hydro, grid supply is then not necessary. An energy utility should then be capable of utilizing this situation to be able to vary the electricity tariff to reflect these supply periods. Given that hydro provides the base-load electricity supply, and the electricity has to be supplied as generated, with no form of storage it is thus expected to be online all the time. It is also expected that the energy cost when the utility grid and hydro are contributing to the supply should be cheaper than when the solar generators are dispatched to the supply. These will give two sets of real-time prices which can be implemented by the energy utility in a time-of-use tariff scheme.

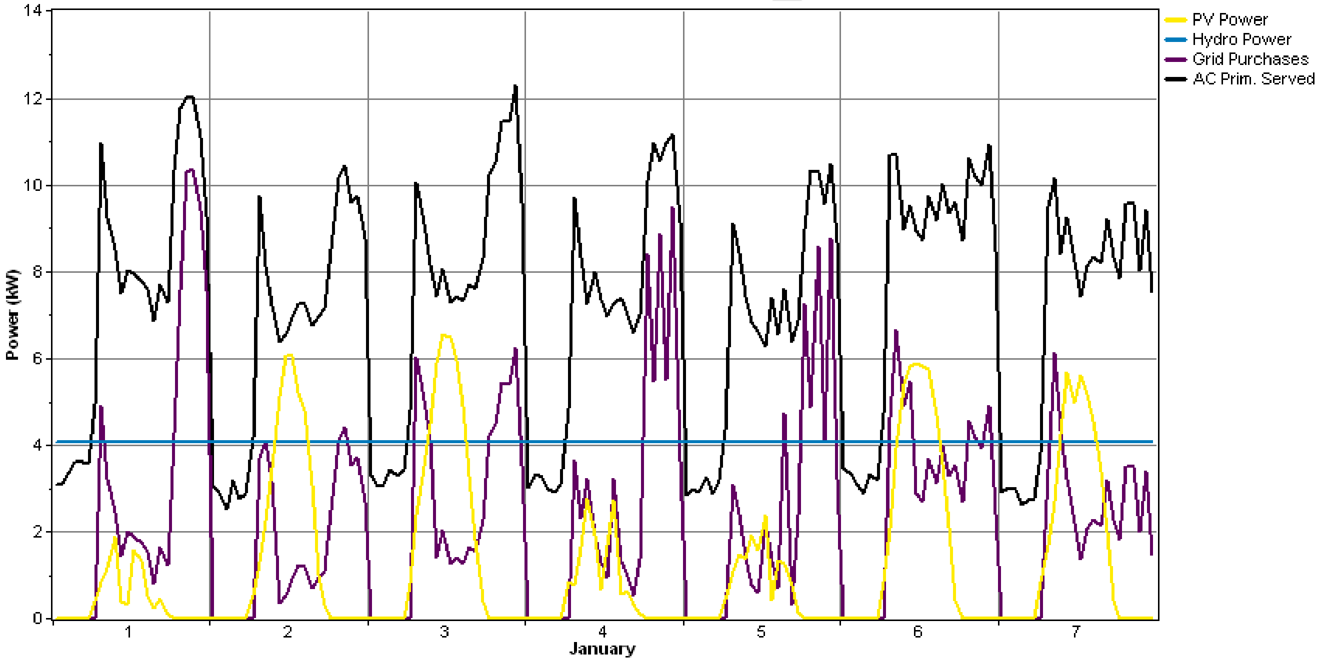


Figure 46: Grid-hydro-PV one week demand-supply situation

5.4 Application of Smart Grid Technologies in Mini-grid Systems

According to (Shang W T & Redfern M A, 2011), "*a smart grid employs communications, innovative products and services, together with intelligent monitoring and control technologies to:-*

- *Facilitate connection and operation of generators of all sizes and technologies.*
- *Enable the demand side to play a part in optimizing the operation of the system.*
- *Extend system balancing into distribution and the home.*
- *Provide consumers with greater information and choice of supply*
- *Significantly reduce the environmental impact of the total electricity supply system.*
- *Deliver required levels of reliability, flexibility, quality of supply and security of supply."*

For a more advanced mini-grid, the system offers the opportunity to implement / test the applicability of smart grid technology in rural hybrid mini-grids. Smart grid functionalities include Advanced Distribution and Transmission Operation, through advanced SCADA systems, and through such functions as (Xue-song, et al., 2010):

- Advanced Distribution Operation with the goal to achieve automation of all control devices and switches in power distribution, through;
  - Advanced Distribution Automation;
  - Automatic voltage and reactive power control system and power management;
  - Real-time monitoring of Distribution information and automatic demand response;
  - To predict and control real-time status of power distribution system;
  - Distributed energy operation;
  - Distribution system asset management.

- Advanced Transmission Operation (ATO) with the aim of achieving intelligent transmission, focusing on congestion management and reducing the risk of large-scale outages.

The most prevalent of smart grid technologies is the Automated Metering Infrastructure (AMI) (Saint, 2009). AMI is smart metering technology that allows information to flow between the energy utility and the consumer domains. This allows real-time pricing signals to be shared between the utility and the customer, providing for a system in which consumers can adjust there energy consumption behaviors to periods when they can save money. Other functions offered by AMI include power quality detection, remote switching function and pre-paid fees function. This smart technology has been utilized by larger, more advanced utilities in developed countries to implement time-of-use and real-time pricing schemes in various residential or industrial settings. The onus is to translate these benefits to rural settings where the consumers have greater incentives to save money. Such a grid connected mini-grid system, utilizing a variety of generation technologies presents an opportunity to test out the applicability of such a technology.

In distributed generation systems, the power is generated and delivered close to its point of use. With grid connected systems, distributed generation provides continuity in supply during network disturbances which result in the loss of the grid connection. As always such opportunities come with a series of challenges, for which smart grids, associated component systems and innovation, can offer solutions (Shang W T & Redfern M A, 2011).

6. CONCLUSION, DISCUSSION AND RECOMMENDATIONS

6.1 Conclusion

Hybrid mini-grids carry a promise of reliable, affordable and sustainable rural electrification. These systems are capable of providing 24-hour grid quality electricity; they are reliable, operate at better efficiencies and offer flexibility in future system planning and operation. They are well suited for distributed generation as they manage the conflict between the preservation of natural resources and economic development. Through utilizing a blend of conventional diesel generation with the freely available renewable resources in remote locations, these systems have the potential to address the electricity needs of rural communities in a reliable, environmentally sustainable, and economically viable manner.

In this study, a systematic approach to the design of a hybrid mini-grid system for Wanale village in Eastern Uganda was presented. Resource availability was established, a short-term demand profile was estimated; and based on the available hydro and solar resources, generators and associated components were chosen for the mini-grid system design. Using HOMER software, different configuration options of the generation systems were simulated to establish the best design for a sustainable hybrid electric power system. This was based on a number of factors:

1. The ability of the electricity supply to match and satisfy the demand, this was based on the resource allocation in the village (hydro and solar);
2. The reliability and efficiency in operation of the system (the system's capacity to match and satisfy the village demand);
3. And the affordability of the system to the consumers (reliable supply at the least energy cost)

6.1.1 System design

It was thus established that the most effective hybrid mini-grid configuration would include a supply system utilizing hydro, solar PV, with battery energy storage and a diesel generator providing the backup. This system was demonstrated to offer the least cost of energy for the required quality and level of service. The system's supply was shown to better match the village demand compared to the others as shown in table 6. And as shown, the hybrid mini-grid system combining hydro + PV + Battery storage + a diesel generator provides the required level of service at the least energy cost, meeting the village demand.

Table 6: Mini-grid configuration comparisons

Supply Configuration	Initial cost ($)	COE ($/kWh)	Capacity shortage (%)
Pico-hydro only	11,000	0.034	57
Hydro + Diesel generator	15,000	0.394	0
Hydro + PV + Battery	41,111	0.128	47
Hydro + PV + Battery + Diesel	51,979	0.301	0

6.1.2 Impact of energy storage

The role of energy storage in hybrid mini-grid system design and operation was also demonstrated to offer additional operational advantages. Two system designs were simulated to demonstrate the advantages offered by the presence of energy storage in the system design. Some of these are shown in table 7.

Table 7: Role of energy storage

Configuration	Initial cost ($)	COE ($/kWh)	Surplus electricity (%)	Diesel fuel consumption (l/yr)	CO2 emissions (kg/yr)
Hydro + PV + diesel + Battery storage+ Diesel	51,979	0.301	2.41	7,470	19,672
Hydro + PV + Diesel	85,890	0.365	28.5	8,809	23,196

As observed in table 7, with the presence of battery energy storage, the system initial capital costs are significantly lower. This is because system components are optimally sized to match the demand, while in the absence of energy storage some of the generating components have to be over-sized in order for the system to be able meet the peak supply. This is also reflected in the comparison in the amount of surplus energy in the two systems, with the absence of energy storage in one system resulting in a lot more surplus energy. Further more, the diesel generator uses significantly less fuel in the presence of energy storage and thus emits less carbon-dioxide. Consequently, the presence of energy storage will also lower the overall energy cost of the system.

6.1.3 System affordability

It was also established that although this system offered quality service, the energy cost was still too high in comparison to the residential grid tariff in Uganda. And given that rural consumers are further constrained by lower incomes, alternative funding mechanisms are thus necessary for affordability, with recommended support coming from renewable energy funding schemes such as the Renewable energy Premium Tariff (RPT) and the Global Energy Transfer Feed-in-Tariff (GET-fit). These could help in the structuring of a tariff that is affordable for rural consumers, thus enabling financial viability for rural electrification projects.

Alternative hybrid mini-grid configurations and operational scenarios were then investigated. Including an analysis of a variable pricing model than can be applied to hybrid mini-grids, to enable consumers save on their energy cost function. A scenario was also presented for the future extension of the electricity grid to the village. This could transform the system into a grid connected mini-grid, able to utilize grid supply when available, and/utilize its own generators when necessary. Other scenarios involving the incorporation of technologies such as fuel cell and Smart Grid are also outlined.

6.2 Discussion

Software models generalize the operation of a mini-grid system, and although a number of operational scenarios are simulated to determine optimal system operation at a particular cost, many factors have to be considered in the implementation of an electrification project. More importantly, rural electrification is an expensive undertaking which does not always guarantee success in the long-term. Many systems though technically sound, have been mainly constrained by finances and mismanagement, causing past failures. Life cycle cost analysis is not full proof as many conditions on the ground are ignored or undervalued by desktop surveys. Donor or government involvement in rural electrification projects goes along way in guaranteeing a certain level of success. And given that hybrid mini-grids have been shown to offer a superior level of electricity service than previous mini-grid technologies, this allows for an additional advantage to the rural electrification process.

Rural consumers are by nature conservative customers, they earn low incomes and are thus sensitive on how they spend their hard earned money. And although they may understand the advantages electrification has to offer, they will trade cautiously on the cost of the service, and will look out for the best way to save money. Therefore, in the event of electrification, innovativeness is necessary in ensuring that the electricity tariff is low enough to entice rural consumers to initially take up the energy service. But also, community participation is important in ensuring the success of the project, as their input offers a more solid foundation on the needs and views of the people. All these factors need to be considered in the prefeasibility phase of the project before any decision to implement is made.

6.3 Recommendations

The biggest huddle in rural electrification is the affordability of the services to the rural consumers. Through various models and pilot projects, hybrid mini-grid systems have shown to be technically adept to providing quality, reliable and affordable energy services, but more research is needed especially;

- Given that renewable energy technologies are still initially more expensive in comparison to the alternatives. The corresponding energy costs are high. With current research trends, this should change in the nearby future. Locally designed and fabricated renewable energy technologies, displace the cost and need for importing system components.
- There are also still plenty of research opportunities in more efficient and reliable power conditioning devices, also energy storage technologies are still progressing towards better energy densities and conversion efficiencies, and lower maintenance needs, as demonstrated by technologies such as fly wheels, ultra capacitors and advanced batteries of lithium, sodium, and flow batteries. Energy storage has an important role in renewable energy applications, and better storage technologies will lead to more reliable hybrid mini-grid system operation.
- Also hybrid mini-grids require trained personnel for operation. Through community participation, implementers should be in a position to organize and train a few community members on the day-to-day technical aspects of operating the system. This will ensure system operational stability even in the absence of the regulators.
- Most importantly, a viable financial model needs to be developed to ensure economic sustainability of rural electrification projects. Many of these systems struggle to survive without donor participation or government subsidies. A sustainable economic structure can be structured around mechanisms such as renewable energy funding schemes, enabling the commercial viability of rural renewable energy electrification programs.

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APPENDIX A

A 1: Modeling the Wanale demand

						total consumption			
type	**Number**	**Time Of Use**	**number of owners**	**appliances**		**rating (W)**	**day (W)**	**night (W)**	**lights out**
Households	**80**								
Residential load									
Houses	68	7pm-11pm		2	indoor lights	14		1904	
		7pm-6am		1	outdoor light	14		476	476
		6pm-11pm	34	1	TV	75		2550	
		7am-11pm	68	1	radio	30	1020	1020	
		24h	10	1	small fridge	120	1200	1200	1200
		7am	10	1	small boiler	500			
			10	1	flat-iron	1000			
						weekday	2220	7150	1676
					total	weekend (TV)	2550		
Commercial load									
Shops	5	7am-10pm		1	indoor light	14	70	70	
everyday (7am-10pm)		7pm-10pm		1	outdoor light	14		70	70

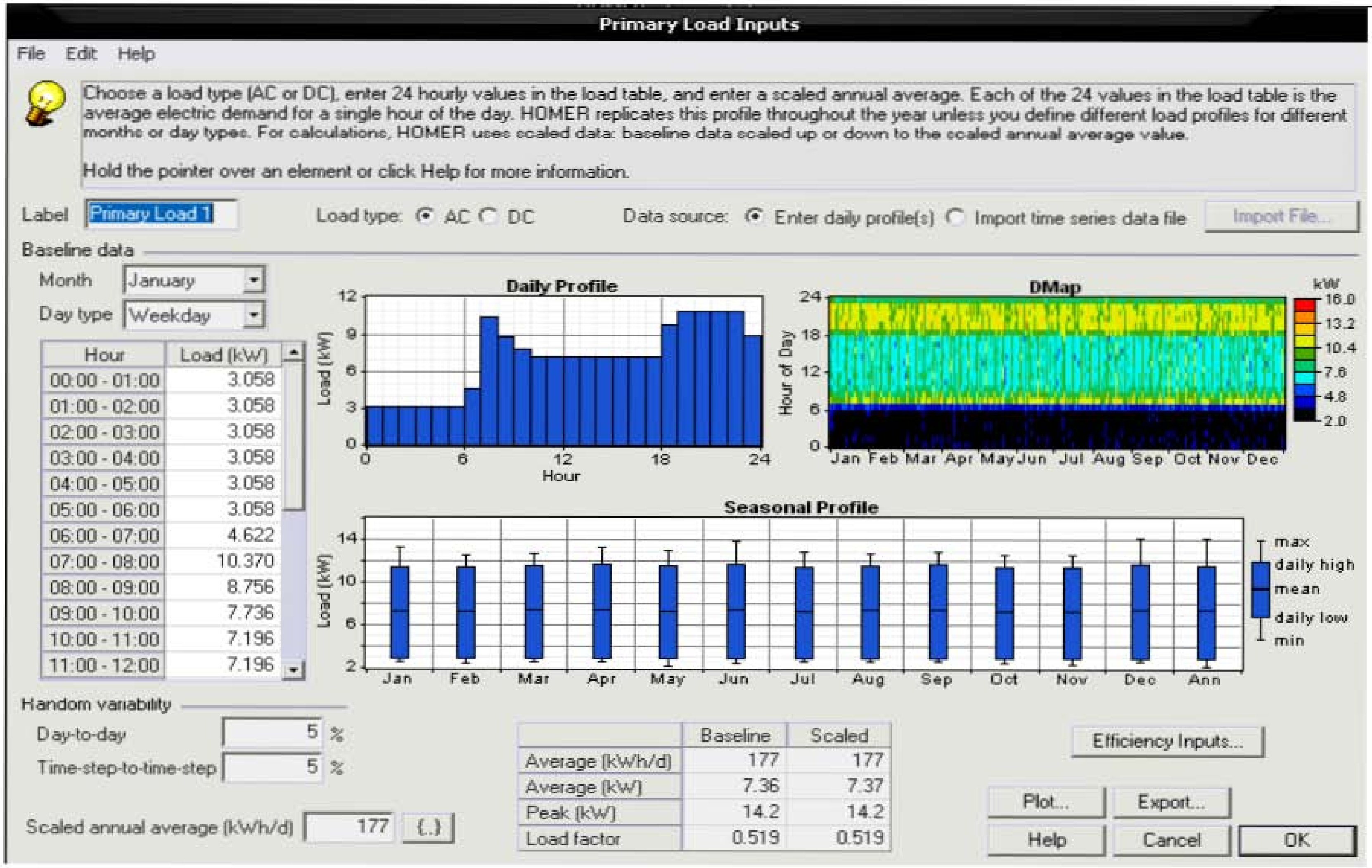
		24h	2	1	small fridge	120	240	240	240
		7am-10pm		1	small radio	30	150	150	
					total		460	530	310
Restaurants	2	8am-7pm		1	indoor light	14	28	28	
everyday (8am-8pm)		7pm-7am		1	outdoor light	14		28	28
		24h		1	small fridge	120	240	240	240
		8am-8pm		1	small radio	30	60	60	
		2h/day		1	small boiler	500			
					total		328	356	268
Bar	2			1	indoor light	14		28	
weekday (8am-11pm)		7pm-7am		2	outdoor light	14		56	56
weekend (8am-2pm)		8am-11pm		1	big radio	150	300	300	
		24h		1	fridge/freezer	200	400	400	400
					total		700	784	456
Video show center	2			1	indoor light	14			
everyday (10am-10pm)		7pm-7am		2	security light	20		80	80
weekend (8am-10pm)		10am-10pm		1	big radio	150	300	300	
		10am-10pm		1	TV	100	200	200	
		10am-10pm		1	Video	20	40	40	
					total		540	620	80

Saloon	2								
everyday (8am-10pm)		8am-10pm		2	inside lamps	20	80	80	
		7pm-7am		1	outside lamp	14		28	28
		8am-10pm		1	hair drier	500	500	500	
		8am-10pm		2	shaver	10	20	20	
		8am-10pm		1	small radio	30	60	60	
					total		660	688	28
Fuel pump (7am-6pm)	1								
		24h		1	security lamp	20		20	20
		7am-6pm		2	pump	750	1500		
		7am-6pm		1	small radio	30	30		
					total		1530	20	20
Dispensary	1	6am-10pm		2	inside lamps	28	28	28	
every day (7am-10pm)		7pm-7am		1	outside lamp	20		20	20
		24h		1	bigger fridge	200	200	200	200
		6am-10pm		1	small radio	30	30	30	
		6am-10pm		1	small boiler	500	500	500	
					total		758	778	220

A 2: Modeling the Wanale Demand

Wanale load						
hours	**Residential load (KW)**	**Residential load (weekend)**	**Commercial load (KW)**	**Commercial load (Weekend)**	**Total load (kW)**	**Total load (weekend) (kW)**
1:00	1.74	1.74	2.082	2.082	3.058	3.386
2:00	1.74	1.74	2.082	2.082	3.058	3.058
3:00	1.74	1.74	2.082	2.082	3.058	3.058
4:00	1.74	1.74	2.082	2.082	3.058	3.058
5:00	1.74	1.74	2.082	2.082	3.058	3.058
6:00	1.74	1.74	2.082	2.082	4.622	4.622
7:00	5	8	5.370	3.370	10.370	11.370
8:00	5	8	3.756	3.766	8.756	11.766
9:00	4	6	3.736	3.746	7.736	9.746
10:00	2.1	3.45	3.758	5.054	7.196	9.746
11:00	2.1	3.45	3.758	5.054	7.196	9.746
12:00	2.1	3.45	3.758	4.238	7.196	9.746
13:00	2.1	3.45	3.758	4.238	7.196	9.746
14:00	2.1	3.45	5.054	4.238	7.196	9.746
15:00	2.1	3.45	5.054	4.238	7.196	9.746
16:00	2.1	3.45	5.054	4.238	7.196	9.746
17:00	2.1	3.45	5.054	4.238	7.196	9.746
18:00	2.1	3.45	5.054	4.118	9.746	9.746
19:00	6.91	6.91	4.42	4.284	10.926	10.926
20:00	6.91	6.91	4.02	3.536	10.926	10.926
21:00	6.91	6.91	4.02	3.536	10.838	10.838
22:00	6.91	6.91	2.082	2.41	10.838	10.838
23:00	6.91	6.91	2.082	2.41	8.860	8.860
0:00	1.74	1.74	2.082	2.41	3.058	3.386

APPENDIX B



Choose a load type (AC or DC), enter 24 hourly values in the load table, and enter a scaled annual average. Each of the 24 values in the load table is the average electric demand for a single hour of the day. HOMER replicates this profile throughout the year unless you define different load profiles for different months or day types. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value.

Hold the pointer over an element or click Help for more information.

Label: Primary Load 1

Load type: ● AC ○ DC

Data source: ● Enter daily profile(s) ○ Import time series data file

Baseline data

Month: January

Day type: Weekday

Hour	Load (kW)
00:00 - 01:00	3.058
01:00 - 02:00	3.058
02:00 - 03:00	3.058
03:00 - 04:00	3.058
04:00 - 05:00	3.058
05:00 - 06:00	3.058
06:00 - 07:00	4.622
07:00 - 08:00	10.370
08:00 - 09:00	8.756
09:00 - 10:00	7.736
10:00 - 11:00	7.196
11:00 - 12:00	7.196

Random variability

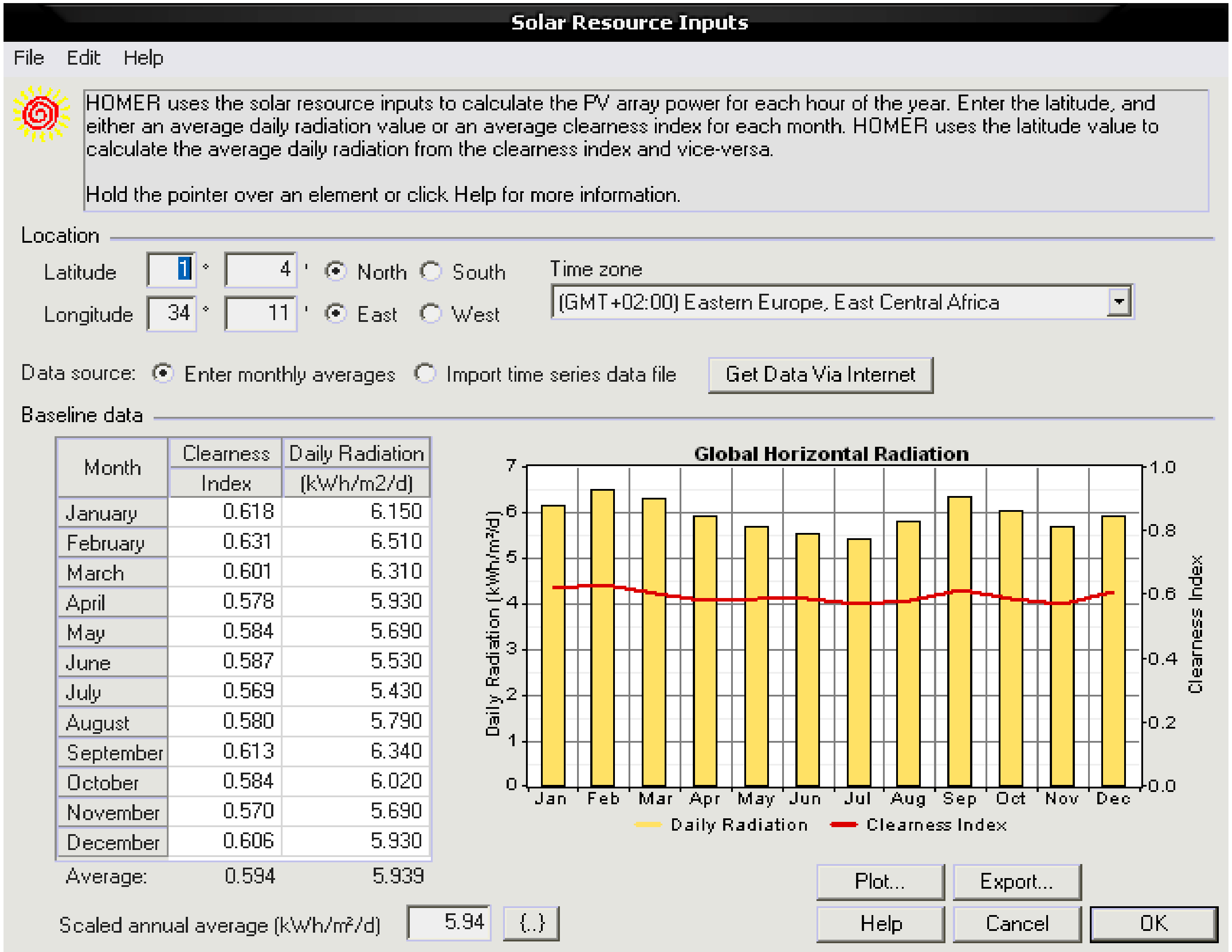
Day-to-day: 5 %

Time-step-to-time-step: 5 %

Scaled annual average (kWh/d): 177

	Baseline	Scaled
Average (kWh/d)	177	177
Average (kW)	7.36	7.37
Peak (kW)	14.2	14.2
Load factor	0.519	0.519

B 1: HOMER Wanale load input



HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude 1 ° 4 ' ● North ○ South

Longitude 34 ° 11 ' ● East ○ West

Time zone: (GMT+02:00) Eastern Europe, East Central Africa

Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.618	6.150
February	0.631	6.510
March	0.601	6.310
April	0.578	5.930
May	0.584	5.690
June	0.587	5.530
July	0.569	5.430
August	0.580	5.790
September	0.613	6.340
October	0.584	6.020
November	0.570	5.690
December	0.606	5.930
Average:	0.594	5.939

Scaled annual average (kWh/m²/d) 5.94

B 2: HOMER solar resource inputs