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# Considerations for a sustainable hybrid mini-grid system: A case for Wanale village, Uganda

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***Abstract***
*The extension of modern energy services to rural sub-Saharan Africa has continuously provided a challenge to energy utilities. The continued reliance on diesel generators for rural electrification is increasingly becoming unsustainable, due to a number of factors, among which includes their high fuel dependency, and the uncertainty surrounding the price and availability of fossil fuels. While the influx of renewable energy technologies has provided a means for providing off-grid electrification services, the intermittent nature of renewable resources poses a challenge, as energy generation does not always coincide with usage. Through a combination of renewable energy technologies, energy storage, and conventional diesel generation, a hybrid mini-grid system is able to achieve synergy in operation, hence providing a reliable means of extending electricity services to rural consumers. In this paper, a hybrid mini-grid system is proposed for the supply of electricity to a remote village in Uganda. Renewable energy resources are identified, an estimation of the projected village short-term electricity demand is modelled, and using HOMER software, a hybrid mini-grid system is designed, components sized, and the system optimized for efficient and reliable operation to meet the village demand at an affordable cost. A well designed and operated hybrid mini-grid system offers a viable tool for the electrification of even the remotest of areas.*

*Keywords: rural electrification, renewable energy, hybrid mini-grid system*

## 1. Introduction

The absence of electricity greatly impacts on the lives of many people in Uganda. The government faces the challenge of providing reliable electricity to most of its population. The share of people connected to the national grid in Uganda is currently at 15%, of which, only 5% of the rural population has access to electricity (MEMD, 2012). 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 in their search for rural electrification options (Ezor *et al*., 2009):

- First and foremost, there is currently insufficient generation capacity to meet the growing electricity demand in Uganda. Therefore, the electricity transmission and distribution utilities concentrate most of the supply to the more reliable customers in urban and developed areas.
- Secondly, the cost of transmitting and distributing electricity to rural areas is high; this coupled with the difficulty of the terrain to most rural areas, low demand, and sparsely populated areas, makes grid extension unfavourable to energy utilities.
- Also, in Uganda, the location of rural areas poses a greater risk to energy losses due to theft (of power and equipment). This also results in difficulties in the monitoring and maintenance of the transmission and distribution network in these remote areas. This increases revenue loss-

es, making it more difficult to justify rural electrification.
- High electricity tariffs also constrain the affordability of rural consumers. This is coupled with their unwillingness to pay for the extension of the service. Thus, there's usually a necessity for government intervention when extending electricity services to poor consumers hundreds of kilometres from the nearest power plant.

Thus, without electricity, 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 who rely on their produce for food and a source of income. Energy services are provided through local resources such as kerosene for lighting, and fuel wood for cooking, with the nearest access to a 'posho' (maize flour meal) shop a two hour walk from the village. For such a community, electrification can act as a catalyst for the social and economic development of the area, allowing the members access to modernized health care, modern communication services, increased availability of light to extend work and engage in income generating activities (MPG, 2010). But in spite of their justifiably low energy needs, the road to achieving electrification can be unfortunately complex and costly.

## 2. Hybrid mini-grid systems

Due to the current global concern over carbon emissions from conventional fossil fuelled power generation sources, many countries are pushing for the integration of renewable resources into the power generation mix. In the past, diesel-powered generators have been the go-to supply option for mini-grid electrification. But factors such as their high maintenance and lifecycle costs (due to their daily fuel needs), high carbon emissions, fluctuating price and availability of diesel fuel, have led to a push for a more sustainable and reliable solution (Moner, 2008). Renewable energy technologies have in recent years become a popular choice for application in remote electrification projects. Among the renewable resources, mini-hydro, biomass, wind and solar have been the standout participants for mini-grid applications. These offer a relatively free and widely available energy resource (Dali, *et al.,* 2010). Resources such as geothermal, hydro and bio-energy are able to provide stability, reliability, and low-cost power generation. However, this is not the case for others such as wind and solar. Implementing these comes with some challenges (Lhendup, 2008):

- Solar and wind resources have daily and seasonal variations. This presents a challenge in matching the available resource with the fluctuating demand, adding to the complexity of deploying them.
- Furthermore, solar and wind energy technologies currently have high capital costs at low conversion efficiencies, resulting in high energy costs for the corresponding generated energy. This provides a challenge of affordability for rural consumers.
- Intermittent resources such as wind and solar, require additional technologies such as energy storage, invertors and regulators in order to optimize for reliable, adequate and efficient power supply.
- It should also be noted that, current cost comparisons between electricity generated from renewable sources of wind and solar, and the equivalent fossil fuel generators, favours the later. This presents a challenge in justifying the alternative to some customers.

Therefore, mini-grids combining both renewable and conventional diesel generation systems could provide a more competitive technical solution, providing a higher level of energy reliability, at a moderately 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 main advantages of such a system would include:

- The maintenance and fuel costs of the generator are significantly 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, in theory, a least-cost supply option.

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). However, hybrid mini-grid systems do 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 topography, local conditions affecting the components, and time series data such as weather.

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. Also the conditions of the area change over time: the demand grows, and grid extension could become a feasible option in the near future. All these factors need to be considered in the preliminary research. The probability of a successful project will also 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 the 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 (Simon & Glanio, 2011).

Through software modelling a generalization of an electricity supply system can be manipulated to better understand the technical behaviour of the system under different conditions. Software models act as a desktop prefeasibility study before the implementation of the actual system.

## 3. Case study: Wanale village

Wanale village is located in the Mbale district, Eastern Uganda at the coordinates 1.0210522N, 34.189341E (iTouchMap.com, 2011), as shown in Figure 3. Uganda is situated in East Africa, with its capital city, Kampala district in the central part of the country. Mbale district lies approximately 245 km 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 45 minutes along Murram Road to Wanale village. 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°C all year round (Frances, 2002). Like most rural villages in Uganda, the members of Wanale are subsistence farmers. 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 7 km away (MPG, 2010). But given the steep nature of the terrain between the access point and the community, the chances of the electricity utility considering grid extension to this village are remote. Thus, a well-designed hybrid mini-grid system could offer a feasible electrification solution to the community's energy needs.

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.

### *3.1 Resource availability*

The members of Wanale recognized the potential for generating hydro-electric power on the Wanale River. A feasibility study, done by Micro Power Group Uganda Ltd on the site, established a design flow rate of 20l/s at 50 metres head. At this flow, a locally fabricated pelton turbine coupled to an induction motor would be able to provide an electrical output capacity of 4.4kW, at an overall efficiency of 50% (MPG, 2010).

Also, Uganda's location along the equator, guarantees that the country receives some of the highest solar irradiation values in the world throughout 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 (Martins, 2005). 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 (NASA, 2004). HOMER simulates the annualized average solar irradiation value at 5.94kWh/m$^2$/day as shown in Figure 1.

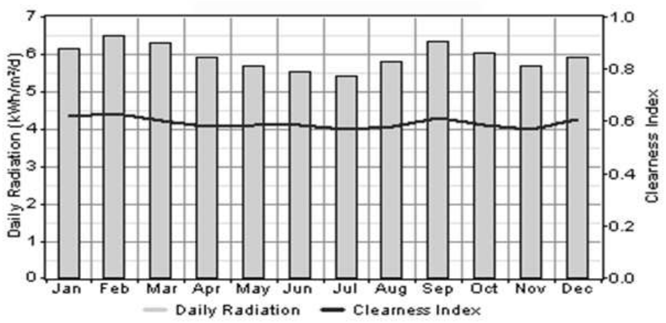


**Figure 1: Homer simulation of Wanale's annual solar irradiation**
*(NASA, 2004)*

### *3.2 Demand*

In the pre-feasibility analysis of the location, it was established that there existed about 80 households

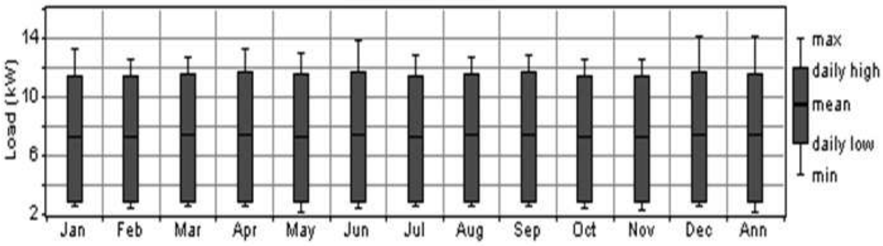


**Figure 2: Homer simulation of Wanale load profile**
*(MPG, 2010)*

within a 1 km 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. An estimate of the short-term demand forecast at Wanale was then 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.

A total load profile was 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 2, presenting Wanale's daily demand at 144kWh, with a peak load of 14kW.

This load is observed to be greater than the available supply capacity of 4.4kW from the design supply of the Pico-hydro plant. Thus different supply configurations are investigated to determine the optimal supply system to meet the electricity demand at Wanale village. Electricity supply is based on available resources of hydro and solar. Also included in the design are battery energy storage, and a diesel generator. The objective is to achieve the most reliable system at the least Cost of Energy (COE).

### *3.3 Hybrid mini-grid system design*

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 (Bala & Siddique, 2009). 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 (NREL, 2005). The system configuration used by HOMER for the design simulations is based on the "parallel" architecture as shown in Figure 3.

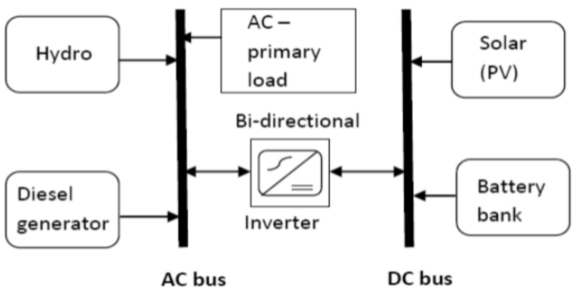


**Figure 3: 'Parallel' Hydro-PV-Battery-Diesel hybrid system**
*(HYRESS, 2008)*

This 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 acting as a DC-AC (Direct Current to Alternating Current) converter (inverter) under normal operation (HYRESS, 2008).

### *3.4 HOMER 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 Table 1 is the cost and technical information for the Wanale hybrid mini-grid system design. Preliminary studies done by (MPG, 2010), established the Pico-hydro plant for 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 (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 remote location, and thus ragged terrain of the village and surrounding areas.

### *3.5 HOMER simulation results*

The presence of hydro resources at Wanale guarantees a base-load supply of electricity, but the capacity would not be enough to cater for the projected short-term village demand. As shown in Figure 4, with only the Pico-hydro supplying electricity, the cost of energy (COE) would only be $0.034/kWh, but the system would incur a capacity shortage of over 57%, meeting less than half of the village's annual demand.

**Table 1: Technical and cost data considered for the hybrid power system**
*(Akyuz, et al., 2010; Simon & Glanio, 2011)*

| *System* | *Parameter* | *Unit* |
|---|---|---|
| PV | Capital cost (US$/kWp) | 2,822 |
| | Replacement cost (US$/kWp) | 2,822 |
| | Operation & maintenance | |
| (US$/yr) | 0 | |
| | Life time (yr) | 25 |
| Hydro | Capital cost (US$) | 11,000 |
| | Available head (m) | 45.29 |
| | Design flow rate (L/s) | 20 |
| | Efficiency (%) | 50 |
| Diesel generator | Capital cost (US$/kW) | 400 |
| | Replacement cost (US$/kW) | 400 |
| | Operation & maintenance | |
| (US$/hr) | 0.15 | |
| | Life time (year) | 10 |
| | Diesel price (US$/l) | 1.3 |
| Converter | Capital cost(US$/kW) | 1,445 |
| | Replacement cost (US$/kW) | 1,445 |
| | Operation & maintenance | |
| (US$/yr) | 0 | |
| | Life time (yr) | 15 |
| | Efficiency (%) | 90 |
| Battery storage 6FM200D | Type | |
| | Capital cost (US$/kW) | 800 |
| | Replacement cost (US$/kW) | 600 |
| | Operation & maintenance (US$/yr) | 15 |

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

| 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 4: HOMER simulation results for hydro supply**

This system is therefore insufficient to meet the available demand, and additional generators and resources are required to match the load.

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

*Case 1: Hydro + diesel generator*
In this configuration, the Pico-hydro plant provides the base-load 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 has been a configuration of choice in many mini-grid installations involving small hydro systems.

As shown by the results in Figure 5, the optimal system design would include the addition of a 10kW diesel generator to the 4.4kW Pico-hydro supply, at an initial cost of $15 000. With the current diesel price in Uganda averaging $1.3/liter, the Total Net Present Costs (TNPC) would equal $316,193, resulting in COE of $0.458/kWh. As observed in the sensitivity analysis in the figure, the energy cost is responsive to the variations in the fuel price, with lower diesel prices corresponding to lower COE, while rising fuel costs increase the operating costs of the system, resulting in higher energy costs.

*Case 2: Hydro + solar + energy storage*
In this configuration, hydro provides the base-load electricity supply, 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.

As shown in Figure 6, the optimal system design includes; in addition to the 4.4kW supply from hydro, an additional 8kW from PV, with a 4 battery bank (6FM200D) energy storage facility (9.6kWh nominal capacity).

This system has a higher initial cost ($41 111) than the system in case 1 due to the cost of the PV

| 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 5: HOMER simulation results for Case 1**

| | 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 6: HOMER simulation results for Case 2**

| | PV (kW) | Hydro (kW) | 6FM200D | Conv. (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Capacity Shortage |
|---|---|---|---|---|---|---|---|---|---|---|
| | 3 | 4.44 | 50 | 1 | $ 140,221 | 2,576 | $ 167,715 | 0.403 | 1.00 | 0.48 |

**Figure 7: HOMER simulation results for Case 2 with 50 batteries for energy storage**

| 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 8: HOMER results for Case 3**

panels, but it also offers lower life cycle costs, at a Total Net Present Cost of $60 429, resulting in a COE of $0.128/kWh. But although this system provides a low energy cost, the system capacity would be insufficient to meet the total demand, incurring a 40% capacity shortage. Even at an increased number of batteries, optimal system operation will always incur a capacity shortage as shown in Figure 7. This indicates that the resources are not matched to the energy storage, and further simulations do not change this situation.

*Case 3: 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. And as shown in Figure 8, at a fuel price of $1.3/liter, the hybrid mini-grid system, in addition to the 4.4kW supply from hydro, would include a 7kW PV array supply, a 5kW diesel back-up generator and a 20 battery (48kWh nominal capacity) energy storage facility.

Thus, at a system initial capital cost of $ 55 979 the Total Net Present Costs (TNPC) accumulate to $ 232 291, resulting in a COE of $0.337/kWh, for the price of diesel at $1.3/liter. And as observed in the sensitivity analysis in the figure, the rising fuel prices have a slightly negligible impact on the energy cost as compared to Case 1.

Simulation of the electrical supply properties of the system indicate that as shown in Figure 9, indicate a capacity shortage of less than 1%, meaning that the consumer demand is matched by the available supply.

### *3.6 Results and discussion*

Three configurations of the proposed power supply system for Wanale village have been simulated. Here is a summary of the findings.

**Table 2: Configuration results analysis**

| *Supply configuration* | *Initial cost ($)* | *COE ($/kWh)* | *Unmet load (%)* |
|---|---|---|---|
| Pico-hydro only | 11,961 | 0.034 | 57.4 |
| Hydro + PV + Battery | 41,111 | 0.128 | 40 |
| Hydro + PV + Battery + Diesel | 55,979 | 0.337 | 0 |
| Hydro + Diesel generator | 15,000 | 0.458 | 0 |

- Hydro as a standalone supply system, though cheaper, has insufficient capacity to meet the village demand.
- The system in Case 2 (hydro, solar + battery energy storage) also offers a low COE, but its capacity to meet the village demand is also limited and thus power distribution to the consumers would be unreliable.
- The system in Case 1 (Hydro + diesel generator) offers a more simplified and initially cheaper supply configuration than Cases 2 & 3. But given the system's dependence on diesel fuel, its operating costs are higher and thus the higher COE. Also, its COE is dependent upon the price of fuel, as observed in Figure 5. Higher fuel costs result in a significant rise in the energy cost.
- The system in Case 3 (hydro, solar + energy storage, and a diesel generator) finds the best balance in operation, meeting the village demand at a significantly lower energy cost. Even at increasing fuel prices, the COE changes are smaller (Figure 8) compared to those in Case 1 (Figure 5).
- Also, because the diesel generator in the system in Case 3 is used less frequently than in Case 1, the operating costs are reduced through

improved system efficiency, resulting in a reduction in fuel consumption, and thus reduced emission levels.

Thus, the hybrid mini-grid system design incorporating hydro, solar + energy storage, and a diesel generator (*Case 3*), offers a reliable and economic supply system, that can best meet the demand at Wanale village. This system can potentially provide relatively cleaner (compared to predominantly based diesel systems) and reliable electricity, and thus meet some of the energy needs of the residents of the village.

### *3.7 Cost analysis*

The electricity tariff for domestic consumers connected to the main electricity grid in Uganda is currently at Ush.524.5/kWh (Umeme, 2013). At a current average exchange rate of 1:2500 USD to Ush, this is = $0.21/kWh. At a mini-grid energy cost of $0.337/KWh, this is = Ush.842.5/kWh. This energy cost is high compared to that of grid connected consumers.

Rural consumers in Uganda are generally poor people surviving on less than a dollar a day. These consumers, though eager to upgrade to modern energy services, are constrained in their expenditure, and are in most cases unwilling to pay for an expensive service. Thus rural electrification initiatives are usually subsidized by the Government or a form of funding mechanism.

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) (Girona, 2008), (Fulton, 2010). These can be used to fully or partially subsidize the system capital costs. Governments have also been known to subsidize the cost of fuel in diesel based mini-grids, though this option has been deemed unsustainable in the long run.

With capital subsidies on the renewable energy generators, the effect on the cost of energy of the system is shown in Figure 10. As observed, the subsidy effect on the capital cost of the individual renewable resource components has an impact on the lowering of the COE. But its effect is more pronounced when both the Solar and Hydro capital costs are subsidized, with the energy cost going as low as $0.29/kWh at 100% subsidy. 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.

## 4. 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. With the intermittent nature of supply from renewable energy resources, available methods to ensure supply, require utilities over size their

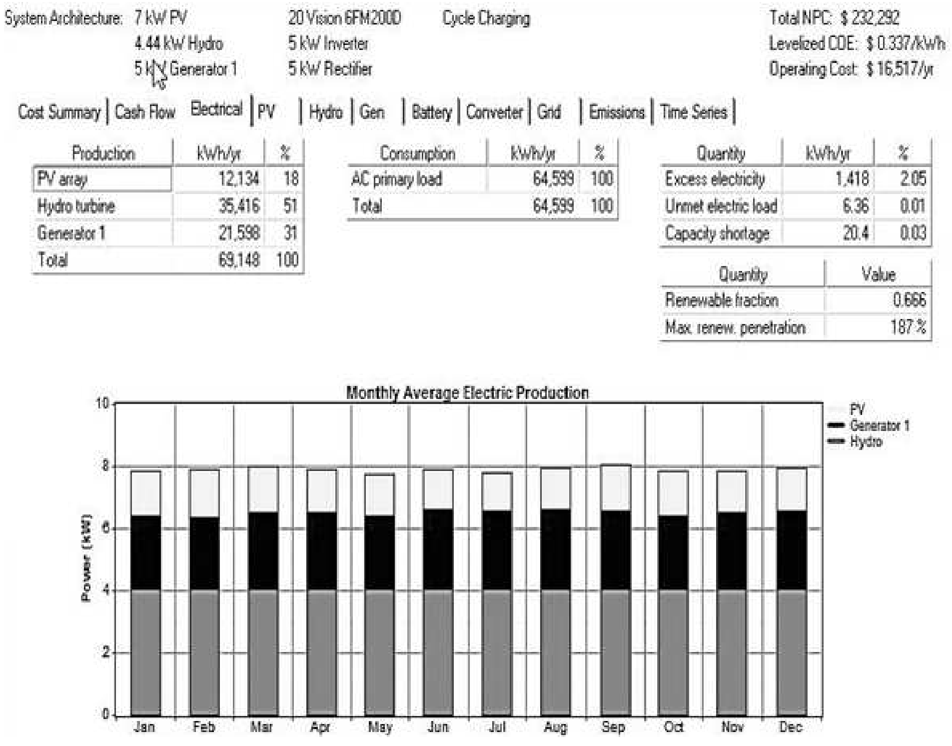


**Figure 9: HOMER simulated electrical supply properties for Case 3**

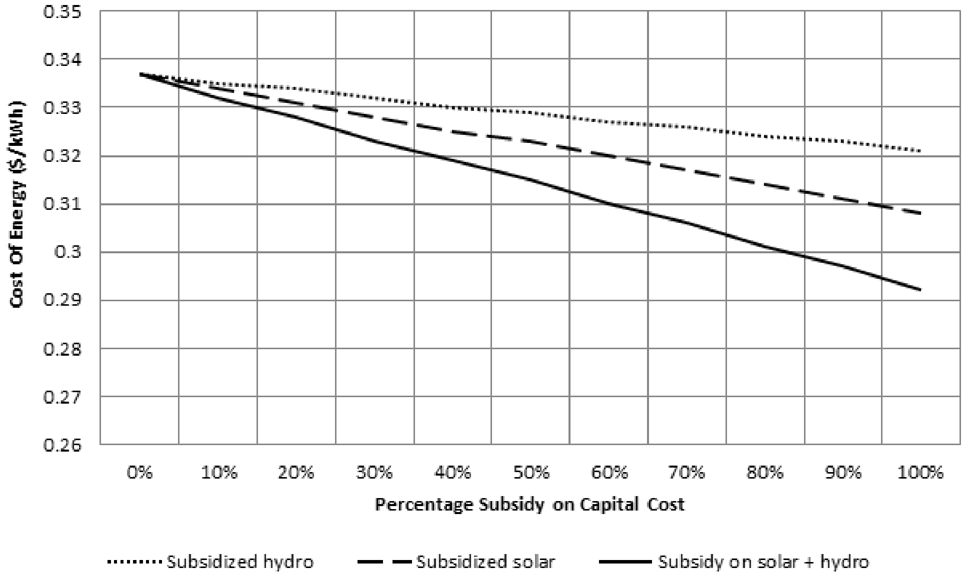


**Figure 10: Effect of subsidizing the system capital costs**

| | Gen (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Diesel (L) | Gen (hrs) |
|---|---|---|---|---|---|---|---|---|
| | 15 | $ 12,000 | 57,314 | $ 744,668 | 0.902 | 0.00 | 28,382 | 8,760 |

**Figure 11: Homer results for a diesel only mini-grid**

supply systems to meet peak demand, and the redundancy of system equipment and/ operation, to cater for demand fluctuations. With power systems currently constrained by fuel economics, and global concerns over emissions from fossil-fuel-based electricity generation, running diesel generators for extended periods is no longer a sustainable solution for meeting daily load fluctuations (Sutanto, 2002).

As can be observed in HOMER's simulation of a diesel only mini-grid in Figure 11, at a fuel price of $1.3/liter, the COE is very high at $0.902/kWh. This is mainly due to high operating costs brought about by fuel consumption of 28 382 liters annually.

This system, though able to effectively cater to the demand of the village, is too expensive in the longer term. This coupled with the associated emissions would make for an unsustainable solution.

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 (Roy & Bagen, 2006).

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. System characteristics in Case 3 are compared to a similar system design without the inclusion of an energy storage facility. This system would take on the form shown in Figure 12, with simulation characteristics shown in Figure 13.

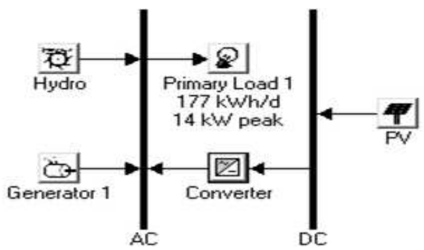


**Figure 12: HOMER hybrid mini-grid system model**

As observed in Figure 12, without energy storage, the hybrid mini-grid system architecture would comprise a 20kW PV array, a 10kW diesel generator and the 4.4kW base supply of hydro. And as noted the electrical supply properties, the amount of excess electricity (28.5%) indicates system oversizing and/ redundancy in system operation to match the fluctuating demand. The impact of energy storage on system operation can quantitatively be evaluated through the values in Table 3, indicative of the different system characteristics.

And as can be observed from the table, the inclusion of an energy storage facility in the hybrid mini-grid design offers a number of operational advantages:

- With energy storage, a smaller size of the diesel generator is sufficient, which operates at a better load factor, and will make fewer starts/year, and

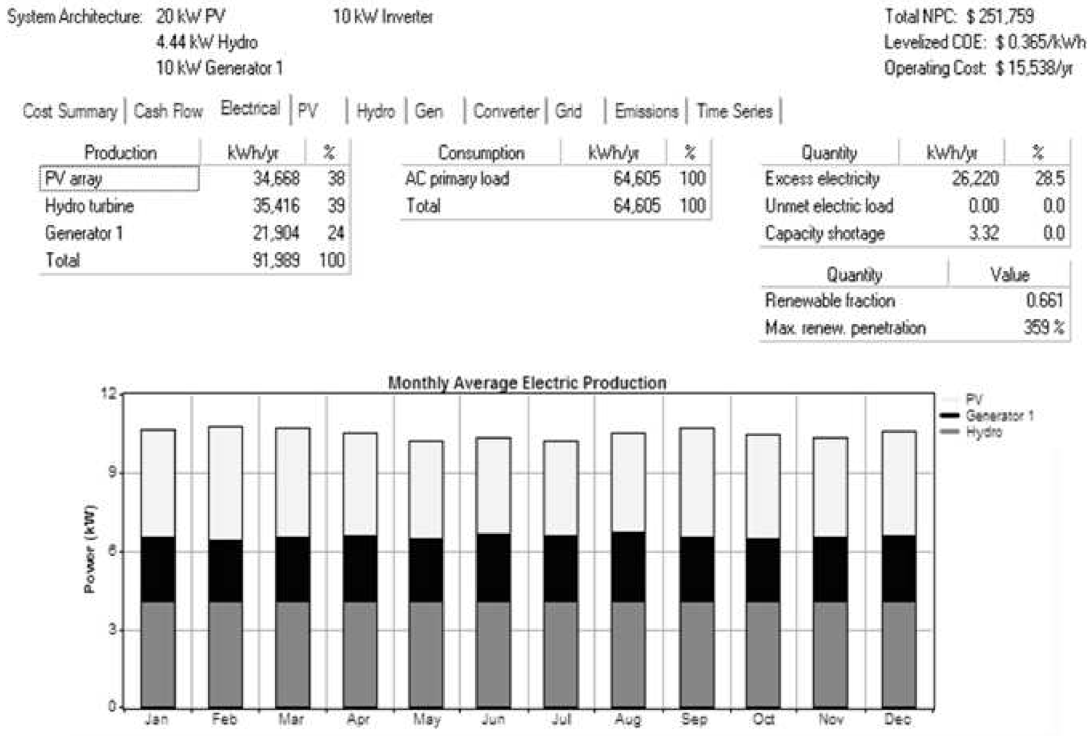


**Figure 13: System electrical supply properties**

**Table 3: Effect of energy storage on hybrid mini-grid system operation**

| | | *With storage* | *With no storage* | *Savings* |
|---|---|---|---|---|
| | | *Values* | | |
| *PV* | Size (kWp) | 7 | 20 | |
| *Generator* | Size (kW) | 5 | 10 | |
| | Number of generator starts/yr | 671 | 745 | |
| | Hours of operation (hr/yr) | 4,803 | 4,166 | |
| | Load factor (%) | 50 | 25 | |
| | Fuel consumption (l/yr) | 7,321 | 8,809 | - 1,488 |
| | Mean electrical efficiency (%) | 30 | 25.3 | |
| *System* | Surplus electricity (kWh/yr) | 1,418 | 26,220 | |
| | Surplus electricity (%) | 2.05 | 28.5 | |
| | Carbon dioxide emissions (kg/yr) | 19,277 | 23,196 | - 3,919 |
| *Economics* | Initial capital cost ($) | 55,979 | 85,890 | - 29,911 |
| | Total NPC ($) | 232,292 | 251,759 | -19,467 |
| | COE ($/kWh) | 0.337 | 0.365 | |

is thus more efficient in operation.

- Another 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 are savings on fuel consumption, and thus the associated operation 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 initial cost of the system;

Thus energy storage is an essential component of a hybrid mini-grid system incorporating renewable energy and conventional diesel generation. With energy storage, the electricity supply system will be more efficient in matching the resources to the demand, thus improved reliability, and will therefore have lower operating costs and life cycle costs, resulting in a lower energy cost.

## 5. Discussion

The decision to implement a mini-grid system in a rural area such as Wanale is often made, based on among other factors, a comparative basis with the cost of extending the electricity grid. But other factors also play an important role in the decision making (Ezor, *et al.,* 2009):

- The difficulty in the terrain between the grid access point and the location,
- Profitability of the project, given utility concerns such as the theft of power, transmission equipment and losses, given the remoteness of rural locations.

Therefore, although grid electricity offers a number of advantages in the quality and stability of supply, a properly designed and operated hybrid mini-grid system is capable of providing 24 hour grid quality electricity. Wanale's location offers a convincing case for the implementation of a mini-grid, while offering flexibility in future system expansion and operation. With the current global shift towards clean energy sources, these systems offer an opportunity to explore electricity generation options with renewable energy resources, while also providing opportunities to extend modern energy services to rural consumers.

## 6. Conclusion

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 most appropriate design. This was based on a number of factors:

1. The ability of the electricity supply to match and satisfy the demand;
2. The reliability and efficiency in operation of the system;
3. And the affordability of the system.

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 back-up. This system was demonstrated to offer the least cost of energy for the required quality and level of service. And the system's supply was shown to better match the village demand compared to the others. But despite the many benefits of the system, the energy cost was still too high in comparison to the residential grid tariff in Uganda, and alternative funding mechanisms would therefore be required to provide financial support in the form of subsidies, to enable system financial viability.

Hybrid mini-grid systems, when properly designed can be a powerful technology for achieving rapid rural electrification, especially in sub-Saharan Africa where the biggest portion of the population resides in remote villages.

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