Title: An Economically Viable PV Hybrid Micro-Grid Model for Remote Villages in Developing Countries

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Abstract: Africa contains a significant portion of the world's population who are in energy poverty. The Sub-Saharan region, in particular, is laden with low electrification rates and high energy prices. This restricts affordable and reliable energy access, specifically in urban slums and rural communities. Decreasing component costs, such as photovoltaic (PV) modules have allowed for renewable energy systems to compete with fossil fuels and in some cases, can also gain an economic as well as environmental advantage. This study looks at the feasibility of incorporating PV into the many existing diesel-fueled mini-grids in Tanzania, offering a hybrid renewables-based system using HOMER software. Using the net present cost (NPC) and levelised cost of electricity (COE) designs were optimised to provide cleaner and cheaper electricity, when compared to the existing diesel counterparts. A hybrid PV-diesel system with battery storage proved the most economical with a COE of $0.29/kWh compared to the diesel-fueled COE of $0.35, a 16% decrease. The NPC for the hybrid model was $1,726,922 compared to $2,056,400 for the diesel model, proving the potential financial benefits of converting mini-grids across Tanzania to renewable energy.

Keywords: *mini-grid, Tanzania, hybrid system, PV-diesel mini-grid, off-grid rural communities.*

1. INTRODUCTION

Energy is a pivotal resource for a society's maintenance, growth and survival. The access to energy services therefore presents a crucial need to the development of a society. According to the IEA, about 17% of the world's population (1.2 billion) lack access to electricity (Internation Energy Agency, 2016), and 1 billion only have access to unreliable electricity networks (United Nations Foundation, 2013), presenting a global challenge of energy poverty.

Africa is home to ~ 1.17 billion people (Worldometers, 2017), where the majority of the world's population lacking in energy access and clean cooking facilities reside (International Energy Agency, 2014), highlighting this vast region as the epicentre of energy poverty. Given its central geographical location, Sub-Saharan Africa in particular, holds an abundance of renewable (solar) resource. It is a wonder why such potential has not been exploited and given its current energy network it further questions why energy access is so erratic. A decentralised approach to expand energy access may in fact provide a realistic and prompt solution. There has been considerable research into suitable solutions for rural electrification in Sub-Saharan Africa, particular for off-grid solar PV, with the falling costs of PV across the globe, PV systems are becoming more widespread and favourable. However, this region has yet to fully utilise this resource and has suffered from costly PV powered electricity owing to political, financial, and technological risks (Baurzhan & Jenkins, 2016).

This paper will focus on providing clean energy access in rural parts of Tanzania, a primary contributor alongside Kenya to the fast-growing economy in east Africa. The rapid growth has presented an increasing demand for reliable electricity and is stretching the region's limited resources. Although the electricity consumption is low in this region it is partly a consequence of the limited coverage by the grid and is not helped by the low electrification rates, which despite having increased in the last decade have lagged behind the population growth. This issue has impacted a lot of energy policy strategies where there is a general objective to enhance the power generation capacities as well as grid extension and reliability.

Tanzania has a growing population of ~ 55 million in 2016 (Worldometers, 2017), with the majority residing in its rural parts; according to the UN only 2% of the rural population have access to electricity. Considering the country's size (945,087 km²) it holds a low population density (~58 people per km²), with pockets of rural communities. 98% of the country's electricity is supplied by the government owned The Tanzania Electric Supply Company (TANESCO) (Tanzania, 2017) which supplies remote areas through a scattering of isolated mini grids. The primary sources of energy come from petroleum, natural gas, of which there is a large reserve in the country's coastal region, and hydropower with some imported energy (~6%) from Uganda and Zambia (Tanzania Energy Situation, n.d.). However, climate change has impacted hydropower significantly and low water levels have hindered the generation creating a stronger dependence on diesel generation. This highlights the country's need for energy diversification and to relieve some of its reliance on hydropower as a means for renewable energy generation.

Most of the energy consumption in Tanzania is from biomass (90%) (United Nations Industrial Development Organization (UNIDO), 2016), predominantly as heat for cooking and industrial/commercial uses such as manufacturing of clay products and brick burning. The heavy reliance on woody biomass is contributing to the depletion of forestry and presents health concerns due to pollution, particularly inside households where it is burned. The pressing need for energy during cooking highlights a key demand for clean energy and hence the supply of renewable means as an alternative to kerosene lanterns and solid fuel fires, which contribute significantly to premature deaths and health issues (United Nations Industrial Development Organization (UNIDO), 2016). The total installed capacity of electricity generation in Tanzania was 1,358MW in 2016 (Tanzania Invest, 2017), the energy sources are predominantly split between hydropower (42%) and natural gas (45%) with a smaller contribution from liquid fuel (13%) (Tanzania Invest, 2017). Considering solar irradiance levels estimating up to an annual 2360 kWh/m² (Joint Research Centre (JRC), 2017), Tanzania is offered an attractive potential to benefit from PV, a resource that has yet to be exploited based on the current installed energy mix.

The dispersed nature of Tanzania's population has meant that rural areas are mainly supplied by diesel-generated mini-grids or micro-grids. In 2016 this equated to ~ 81 MW of installed capacity with 19 generators in 9 different off-grid locations situated in the southern and western regions (Bertheau, et al., 2014). 17 of these are owned by TANESCO with 2 private cooperatives. However, diesel generator imports were worth over $118 million from years 2008-2012, indicating a larger presence of privately owned generators. In 2017 there were a wide scattering of mini-grids powered by a variety of energy sources, Fig. 1 shows these in relation to planned and existing transmission lines. It is possible that these widely distributed diesel mini-grids could be converted to utilise PV, especially as they already have existing technical, economic and financial infrastructures, relieving bureaucratic procedures required for new systems and offer an even higher potential for hybridisation with renewable energies, Bertheau et al. (Bertheau, et al., 2014) (Bertheau, Blechinger, Cader, & Breyer, 2012).

This study aims to attain a financially viable renewables-based mini-grid by retrofitting the existing diesel-fueled grids with a hybrid PV-diesel powered mini-grid in Tanzania. The objectives are to perform a resource and financial assessment to select a rural region to focus on and to develop and size a suitable design that will meet the needs of the people whilst offering a positive Net Present Cost and reasonable levelised cost of electricity (COE) for the producer. The political constraints will be considered throughout the project and will aid the decisions associated to the methods used. Finally, a sensitivity and risk analysis will show how certain parameters will impact the system's NPC and COE.

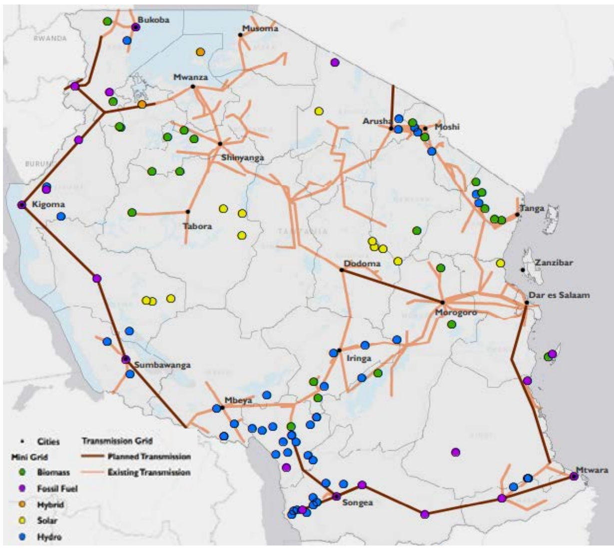

Fig. 1: Mini-grid locations in Tanzania (Energy Data Tanzania 2017).

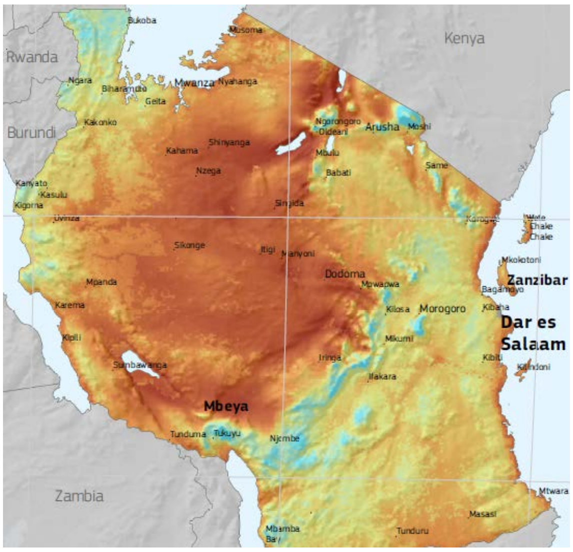

Fig. 2: Solar irradiance map for Tanzania (JRC 2017)

2. METHODOLOGY

2.1. Resource assessment

The economic growth and resource potential were key to establishing the county of focus within Sub-Saharan Africa. Using the PVGIS maps (Joint Research Centre (JRC), 2017) to observe the solar irradiance over the country's footprint in addition to the economic growth, Tanzania was selected. In addition to this the solar irradiance at the locations of the existing mini-grids were also investigated to aid with the village selection, as shown in Fig. 2. Liwale, a small district in the southern district of Lindi with an average daily irradiance of 5 kWh/m²/day and an existing 80 kW (Peng & Poudineh, 2016) diesel-fueled mini-grid owned by TANESCO was selected to observe the hybrid benefits of PV and diesel integration.

2.2. Economic assessment

Tanzania has the second fastest growing economy in Africa, ranking 10th for its GDP in Africa (List of African countries by GDP, 2016). With an increasing demand in electricity and volatile fossil fuel prices, Tanzania can benefit from a reduction of fossil fuel-reliance, a source that accounts for a high share of its GDP expenditure (Bertheau, Blechinger, Cader, & Breyer, 2012). The volatility of the Tanzanian shilling (TZS) has meant that the currency figures throughout this paper are given in US Dollar (USD), a conversion rate of 2,238 TZS = 1 USD, will be used, this also extends to any modelling software used for designing.

Tanzania uses Standardised Purchase Power (SPP) rates particularly for isolated grids or mini -grids which are supported by the Rural Energy Fund (REF), these are levied through the electricity sales or involve international donors (Moner- Girona, et al., 2016). The electricity tariffs range from $0.07 - $0.16/kWh (Energy and Water Utilities Regulatory Authority (EWURA), 2016) with rural SPP mini-grid values as high as $0.33/kWh (Moner- Girona, et al., 2016). The consumers would of course purchase at a much higher rate, particularly those being supplied from mini-grids. It is also important to understand how the diesel costs have great influence in the fluctuations of these prices.

2.3. Governance

Tanzania joined Lighting Africa in 2008, an initiative by the World Bank Group and the International Finance Corporation (IFC), wishing to accelerate the development of clean off-grid lighting in Sub-Saharan Africa. Their focus on quality assurance, consumer education, market intelligence, business and supply chain development and access to finance (Tanzania, 2017), ensures a process is in place for verifying the quality of products. It is to no surprise then that Tanzania is also one of the leading markets for solar lighting products along with Kenya and are also Africa's largest micro-grid markets. In 2005 the Rural Energy Agency and the Rural Energy Fund were established as a result of the Tanzanian government passing the Rural Energy Act, (REA), with the primary goal of overseeing the implementation of rural electrification projects (Moner- Girona, et al., 2016).

As great the potential may be, the situation in Tanzania comes with various challenges. Investment has been hindered due to the notorious reputation of TANESCO, with a vulnerability to corruption and poor credit-worthiness it is heavily laden in debt. It has also failed at competitive pricing due to its lack of business separation; the generation, transmission and distribution are all encompassed in a vertically integrated structure (Kuran, 2016), thus the retail prices have been known to be high. A social tariff of a lower rate is available for those using up to 75 kWh a month, however due to the high connection fees very few can take advantage of such access, these fees have been revised since 2012 and offer a lower rate to rural and urban areas in the effort to increase electrification. With tariffs being regulated by the Energy and Water Utilities Regulatory Authority (EWURA) and approval of the Electricity Act of 2008, the generation and distribution segments have now been opened to industry.

Using an existing diesel-fueled mini-grid owned by TANESCO alleviates the need to undergo new SPP and Independent Power Producer (IPP) agreements, it also allows the model to compare its current emissions from existing diesel mini-grids to the proposed hybrid ones. The financial mechanisms such as methods of payment are assumed to remain the same, with the component quality inspection to be coordinated by the Rural Energy Agency and REF.

2.4. System design

Using the modelling software Hybrid Optimisation of Multiple Energy Resources (HOMER**)**, the PV-diesel hybrid mini-grid design was optimised and compared to its diesel counterpart. The key indicators to determine the best model were the total Net Present Cost (NPC) and levelised Cost of Electricity (COE). The total NPC is the present value of all the costs incurred in the project lifetime (such as capital costs, operation and maintenance costs, fuel costs) minus all the revenue accrued over its lifetime. HOMER uses the Equation 1 to calculate the total NPC:

(1) $$NPC = \frac{C_t}{CRF(i, R_{proj})}$$

Where C_t is the total annualised cost [$/year], $CRF(\,)$ is the capital recovery cost [$], i is the interest rate [%] (for this model 6% is used), and R_{proj} is the project lifetime [years] (25 years for this project). The levelised COE is defined as the average cost per kWh of useful electricity produced by the system, given by Equation 2 in HOMER:

(2) $$COE = \frac{C_t}{E_{p,AC} + E_{p,DC} + E_{def} + E_{grid\ sales}}$$

Where $E_{p,AC}$ and $E_{D,AC}$ are the AC and DC primary load respectively [kWh/year], E_{def} is the deferrable load [kWh/year], and $E_{grid\ sales}$ is the total grid sales [kWh/year].

Load Profile

With limited access to load profile data, the daily fluctuations from the findings of Hartvigsson et al (Hartvigsson, Ahlgren, & Molander, 2015), were used alongside the annual base load of 34 kWh per capita, published on Tanzania's Ministry of Energy and Minerals' Power System Master Plan (Energy and Water Utilities Regulatory Authority (EWURA), 2016). A population figure of 13,378 (last available published figure since 2012) (Brinkhoff, 2017) for rural Liwale was used to identify the total load on the grid. The resulting load profile shown in Fig. 3 gave an estimated daily average of 94 W of electricity consumption per person. This was used as the primary load input needed for the analysis with HOMER.

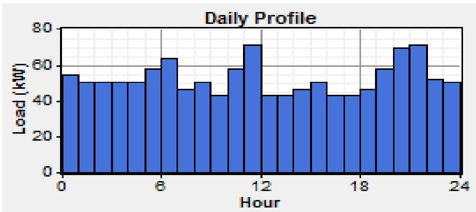

Fig. 3: Estimated load profile for Liwale

PV and Inverter Components

The average price of PV modules in Tanzania of ~ $1/Wp was used, however it is likely that the trade prices would be much lower than, additionally prices would continue to reduce especially as figures in the UK can be as low as $0.3/Wp. The installation, operations and maintenance (O$M) costs were assumed to be ~$0.4/Wp, giving an annual estimate of $16 over a 25-year project lifetime. To size the system, a range from 0 kW (to account for no PV), to 450 kW values were entered in steps of 40 kW, including each 100 and 150 kW step. A general figure for the balance of system (BOS) was used at $1.3/Wp (Moner- Girona, et al., 2016) and was factored into the overall PV capital cost input in HOMER.

Homer can model a converter with both, inverter (DC to AC) and rectifier (AC to DC) properties. To convert the DC power from the PV modules to useful AC power an inverter was included in the model. The capital costs in this study were set to $106/kW for an 8kW inverter and $254/kW for a 12kW inverter, both relating to quotes found in Tanzania, including annual O&M costs at 1.5% of this capital. Sizes ranged from 0 (no converter) to 75kW with a 15-year lifetime.

Diesel costs and generator

The current price of diesel in Tanzania, at $0.82/l (Global Petrol Prices, 2017), was used for understanding the running costs of the generator. Using a diesel generator cost of ~ $267/kW in Tanzania, the installation was assumed to be a ~2%, giving $272/kW. Arguably this cost would be moot if the retrofit system has a functioning diesel generator that does not need replacing soon after the modifications. For the sake of capturing the benefit of new hybrid systems or replacing the generator for this project, the cost of a diesel generator has been included. Sizes from 0 (no diesel generator) to 80 kWh were entered in intervals of 20 kWh.

Battery

The battery is a crucial element to a PV system, theoretically this would negate the need for a diesel generator entirely if energy storage was able to meet the demand when irradiance levels were too low, particularly in the evenings and night. However, the cost of batteries tends to decide how much energy storage would be reasonable for a given project. Low battery prices would allow the PV share to increase as the energy would be stored and later used in a greater capacity.

With a range of batteries costs found from $0.93/Ah (6V) batteries to $1.95/Ah (12V), an estimated figure of $1100 for each unit was used for a 2-string configuration of the pre-loaded battery type Surrette 6CS25P in HOMER. Manufactured by Rolls Battery (www.rollsbattery.com), this has a nominal capacity of 1156 Ah and a lifetime throughput of 9645 kWh, with estimated values of $10/year O&M costs. Quantities varying from 0 (no battery) to 400 were entered in intervals of 5.

2.5. Sensitivity and risk analysis

Using HOMER's sensitivity analysis tool, a range of parameters were adjusted to observe their effects on the system, namely, diesel costs, battery costs and costs for the PV modules.

Diesel costs

To account for the volatility of diesel prices, the diesel costs were varied from the current value of $0.82/l to include, $0.84/l, $0.87/l and $1/l, values that have been experienced in the last year. In addition to this, to understand the implications of higher prices, a maximum value of $1.48/l was used as this was the case in 2011 (Moner- Girona, et al., 2016).

Battery costs

Considering the varying battery costs and their impact to the design, a range of sensitivity multipliers were entered, from 0.8 (to account for prices at ~ $0.76/Ah), to 1.5 (to account for prices at ~$1.43/Ah), to understand their impact on COE as well as renewable energy share.

PV module costs

Decreasing PV costs have made PV a serious competitor with fossil fuels. Considering lower module prices in other countries, it is likely that these would continue to reduce in Tanzania. A sensitivity cost multiplier of 0.78, to account for a 50% decrease in module price alone, was used.

3. RESULTS AND DISCUSSION

The system comprised of the schematic in Fig. 4. Results were categorised into 4 scenarios:

- (i) PV + diesel generator + converter + battery
- (ii) Diesel generator + converter + battery
- (iii) PV + diesel generator + converter
- (iv) Diesel generator

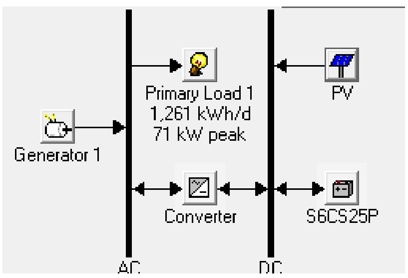

Fig. 4: Schematic of model equipment in HOMER

3.1. Optimised Result

HOMER searches all the feasible configurations and ranks them according to their NPC. The results for this analysis showed the PV hybrid, scenario (i), most favourable with an NPC value of $1,726,922 and COE at $0.29/kWh. Previous estimated COE by an off-grid PV mini-grid in Tanzania have fallen in the range of $0.30-$0.65/kWh (Moner- Girona, et al., 2016) and a decentralised hybrid PV-diesel system in Nigeria by S.M. Adaramola et al. (Adaramola , Paul, & Oyewola, 2014), resulted with a range of $0.35-$0.38/kWh. Other results for a PV stand-alone system from research in South Africa by J. February et al. (February, Nguz Mbav, & Chowdhury, 2013), ranged from $0.30 - $0.52/kWh. The results from this study therefore highlight the suitability of the hybrid model with the current climate and market prices in Tanzania, and coupled with studies across the globe the attractiveness of a hybrid model is ever increasing, particularly when compared to solar home systems, a similar result was found in Bangladesh (Chowdhury, Aziz, Groh, Kirchhoff, & Filho, 2015). The least favourable option was the isolated diesel generator, scenario (ii), with an NPC value of $2,056,400 and COE at $0.35, a 19% increase. Fig. 5 shows a summary of the results for the four scenarios.

PV (kW)	Gen 1 (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen 1 (hrs)
120	60	20	70	$ 349,269	107,769	$ 1,726,922	0.294	0.38	112,968	6,608
	60	20	20	$ 45,769	146,026	$ 1,912,470	0.325	0.00	159,115	8,760
40	80		20	$ 121,209	149,488	$ 2,032,163	0.345	0.14	158,170	8,760
	80			$ 21,760	159,163	$ 2,056,400	0.350	0.00	171,128	8,760

Figure 5: Results summary in HOMER

3.2. Emissions

The corresponding emissions data for each configuration is shown in Table 1. The data identifies a potential saving of 16% for the COE [$/kWh] from the current diesel generator used, in addition to a 34% decrease of CO_2, CO, SO_2 and NO_x emissions each year. These emissions are what often promote PV technology in Sub-Saharan Africa, with the attempt of improving the environment and public health. However, as discussed by Baurzhan et al. (Baurzhan & Jenkins, 2016) the larger contributions to greenhouse gases (GHG) are from household cooking and projects in developing countries discovered that improved cooking stoves were able to reduce the GHG emissions with greater impact. This resulted in a lower cost of reducing CO_2 emissions at $40-$190/tCO_2, compared to the $150-$626/tCO_2 for rural PV electrification (Baurzhan & Jenkins, 2016), albeit predominantly for PV lighting systems. This is a consideration investors and developers must heed when deploying PV hybrid mini-grids with the sole goal to reduce GHG emissions.

Table 1. Emissions data from HOMER

Scenario	PV	Gen 1	Battery	Converter	CO_2 Emissions	CO Emissions	Unburned Hydrocarbons Emissions	Particulate Matter Emissions	SO Emissions	NO_x Emissions
	[kW]	[kW]	[No.]	[kW]	[kg/yr]	[kg/yr]	[kg/yr]	[kg/yr]	[kg/yr]	[kg/yr]
i	120	60	20	70	297,482	734	81	55	597	6,552
ii	0	60	20	20	419,003	1,034	115	78	841	9,229
iii	40	80	0	20	416,515	1,028	114	78	836	9,174
iv	0	80	0	0	450,637	1,112	123	84	905	9,925

3.3. Cash Flow

Although the capital at the beginning of the project is attributed mainly to the PV modules, diesel fuel costs contribute most to the NPC as shown in the cash flow summary in Fig.6. under the generator costs "Gen 1", this is further highlighted by the annual cash flow shown in Fig. 7.

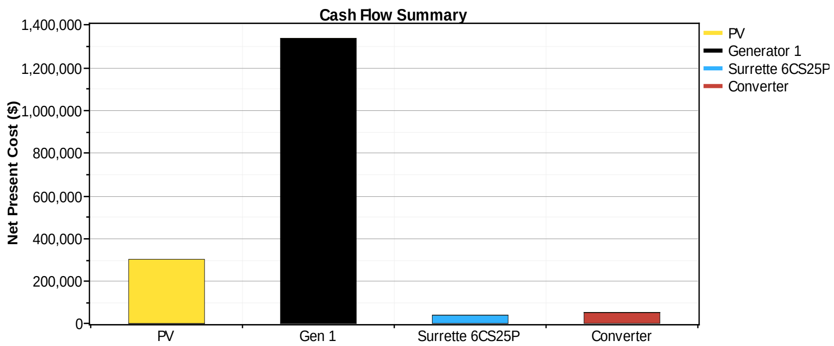

Fig. 6: Scenario i. cash flow summary in HOMER

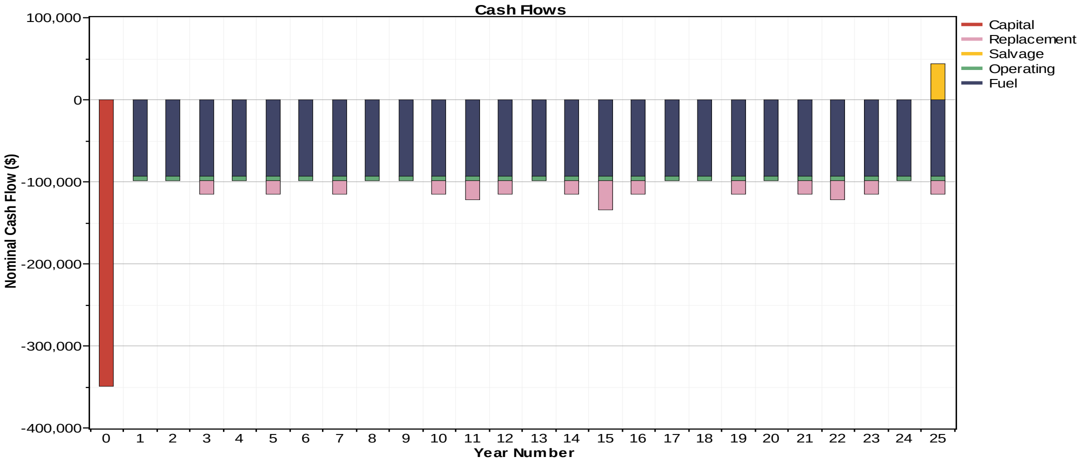

Fig. 7: Scenario i, annual cash flow in HOMER

The initial capital cost is $349,269 with a breakdown of: ~ 79% for PV modules costs, ~10% for the converter, ~6% for the batteries and ~ 5% for the generator. Fig. 7 shows that each year ~ $100,000 is spent on running the diesel generator with smaller contributions made by replacement costs, for the generator, batteries and converter. For systems where there is a greater renewable's share the PV costs are much higher due to the increased capacity, expectedly this also increases the number of batteries used and hence their contribution to the capital and replacement costs increases. This is further supported by works of Bertheau et al. (Bertheau, et al., 2014), where reducing battery prices whilst increasing PV capacity resulted in a PV share of up to ~92%.

3.4. Electricity Production

The presence of the PV modules allowed the reduction in harmful emissions, however at a levelised COE of $0.29, 38% of the power was supplied by renewable means, this highlighted the reliance on the diesel generator for most of the base load as shown in Fig. 8. Although emissions could be further reduced using a PV only system with no generator, the COE deemed unfavourable at $0.57/kWh, however this was reduced to $0.39/kWh when allowing a 10% annual capacity shortfall. Ensuring reliable energy access and providing all the electricity demand were key to this study's objectives and therefore the PV-only model was rejected. However, further study into the types of battery storage, (an essential component for a PV-only model) may improve the COE in the future whilst increasing the renewable energy share of hybrid systems, as shown in the sensitivity analysis.

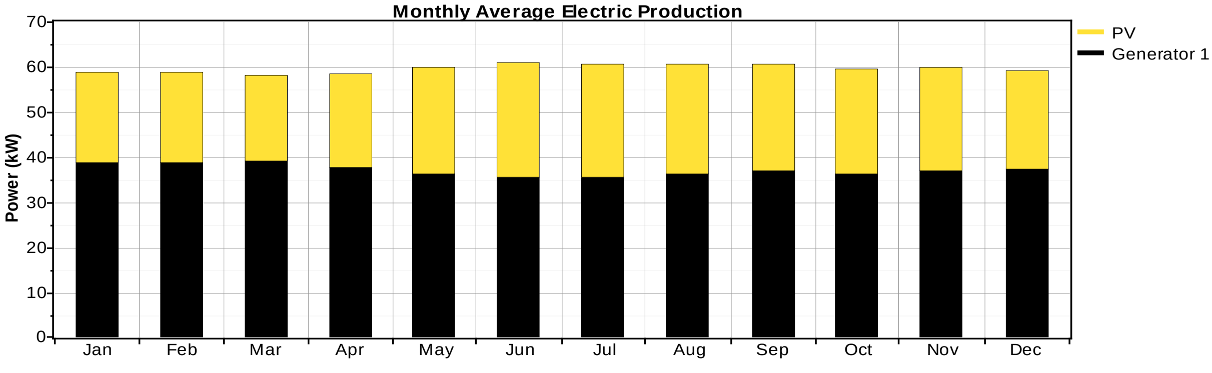

Fig. 8: Scenario i, share of renewable generation

A total supply of 522,700 kWh/year was produced with 38% PV generation and 62% diesel, allowing 100% of the primary load of 460,250 kWh/year for Liwale to be satisfied, this resulted in an annual 39,963 kWh/year (7.65%) excess generation. Tanzania predicts that the average annual base consumption per person, in the region of Lindi, will increase to ~ 102 kWh by 2020 (Energy and Water Utilities Regulatory Authority (EWURA), 2016), this would require a significant increase in capacity (300%). With this in mind, a larger PV capacity will be needed to allow for expansion and may in fact change the optimisation of the design with scope for more battery storage and a smaller or no diesel generator if deemed competitive. If the battery capital cost and PV capacity parameters fit into the threshold discussed by Bertheau et al. (Bertheau, et al., 2014), a renewable share as high as ~90% may be possible, depending on the component prices.

3.5. Sensitivity and risk analysis

The fluctuations of diesel costs, PV modules and batteries were studied to see their effect on the levelised COE as well the implications on the renewable energy share.

Diesel costs vs. PV costs

A COE as low as $0.28/kWh was observed when PV costs reduced to 78% of their original value (representing a 50% reduction in PV module cost). As expected the higher diesel prices increased the COE, reaching highs of $0.45 when diesel was purchased at $1.48/l. At the higher diesel prices, the optimum model suggested a higher PV capacity, increasing the renewable fraction to 44% with a PV installed capacity of 150 kW. Figure 9 shows the impact of diesel and PV costs on the COE.

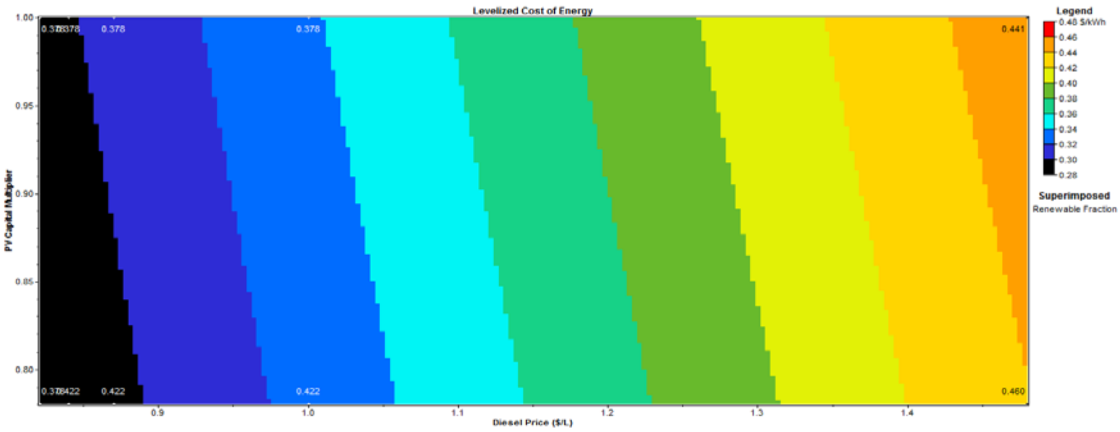

Fig. 9: Scenario i, surface plot of COE with PV vs. diesel

Diesel costs vs. battery costs

Varying the battery costs between 0.8-1.5 times the original values did not show a significant change in the COE, however when running the model at a much lower battery price (going down to as low as 0.1 times), the effects showed that a much higher renewable energy was achievable. At the highest diesel price of $1.48/l a renewable share of 88% was observed, much higher than that observed with the PV multiplier sensitivity analysis. Although battery costs are far from being this low any time soon, the exercise was purely investigative and suggests that energy storage prices and capability will be an interesting factor for the integration of renewables. Fig. 10 shows the results relative to the COE and renewable energy fraction. Previous studies (Bertheau, et al., 2014) investigating maximum energy storage for off-grid systems in the range of 9-24 MWp, found that battery prices sat within a specific threshold range, this threshold determined the point where the renewable share could go beyond ~ 40%, whilst offering a competitive COE. This study indicates that parameters of this system are below this threshold considering the renewable share ranges and installed PV capacity, however the 88% at the lowest battery price indicates further opportunity for investigation with increasing PV capacity, a scenario that may be more attractive in the future, especially as energy demand increases.

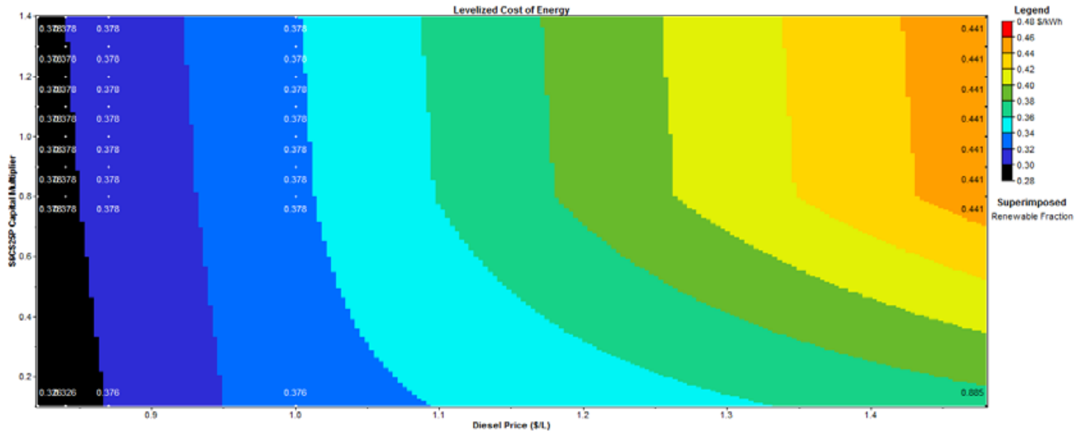

Fig. 10: Scenario 1, surface plot of COE with battery vs. diesel

Limitations to the study

Although the sensitivity analysis investigated the effects of the diesel costs, PV costs and battery costs; key influencing parameters to the model were the component specifications. To gain a better understanding of a proposed project, the specific components selected must be programmed into HOMER for a more accurate analysis. In addition to this, component datasheets with standard testing conditions (STC) are limited in their performance data as Tanzania's environmental conditions would greatly impact the system's behaviour and would therefore need specific life-time testing and monitoring by trained individuals.

From a financial perspective, it is assumed that the interest rate of 6% remains the same throughout the project and the effects of this parameter have not been considered for the sensitivity analysis. The study can be furthered with focus on implementing a hybrid mini-grid independently in Tanzania. This would require further consideration in proposing suitable SPP and IPP agreements, as well as attaining necessary capital funding. Additionally, independent schemes may necessitate payment methods that offer security to the electricity provider so that purchase plans are adhered to by customers.

Private ventures and FIT

Decreasing costs of solar PV have allowed PV systems to compete or triumph over diesel alternatives, particularly for lighting. Tanzania's government has therefore supported a number of off-grid solar PV programmes, via the REA, and has created a contracting mechanism called the Sustainable Solar Market Package (SSMP) which offers supply, maintenance and installation of PV systems for public services such as schools (African Development Bank Group, 2015). It also helps to finance private enterprises through a competitive grant programme, encouraging developing new business models to supply affordable energy to rural areas. Although this includes some incentives and requirements for commercial sale in certain areas, this support does not seem easily accessible nor does it help private ventures particularly those that have established international donors and have developed SPP and IPP agreements. Cases where private firms have signed contracts and got stuck in the lengthy processes have hindered developments.

Feed-in tariffs for off-grid PV have also not offered an attractive incentive for investors looking to finance renewable energy to remote areas, especially if supplying a state owned mini-grid privately is favourable in a certain region. Revising the FIT to be technology specific has been found by Moner-Griona et al. (Moner- Girona, et al., 2016) to be more appropriate, so that better suited technologies are used in the various rural areas depending on the natural resources available. This would need to be coupled with a competitive yet affordable price so that locals can benefit from such a system. A holistic approach to the scattered grids across Tanzania may allow for some areas to reduce sale price in order to remain affordable whilst making up for any losses in other areas that deem more profitable. An improved scheme/FIT would also instil some financial security, allowing investors to recover their capital cost. The increase of these renewables-based mini-grid would also present a socio-economic benefit, allowing rural areas to increase in prosperity with new jobs in operations and maintenance.

4. CONCLUSIONS

After performing the resource and economic assessments stipulated in this study's objectives, the rural area of Liwale in Tanzania was chosen to investigate benefits of a renewables-based mini-grid. Considering aspects of governance and energy policy yielded the opportunity to convert existing diesel mini-grids to hybrid PV-diesel mini-grids, whilst utilising existing structures set up and owned by TANESCO. The decreasing costs of PV, in this case, did not warrant a PV-only mini-grid as the COE was higher at $0.57/kWh and the NPC was $3,353,109 ~ 63% higher than the diesel only option. The study, therefore, considered various designs of mini-grids with PV and diesel. The analysis with HOMER provided an optimum design of a hybrid PV-diesel mini-grid with battery storage at a capital cost of $349,269 with a total NPC of $1,726,922 granting the benefit of a levelised COE of $0.29/kWh, a 16% decrease from a solely diesel-fuel mini-grid providing the same load, Scenario i. At $0.29/kWh, the design achieved a lower COE compared to other hybrid PV grids in Tanzania $0.30-$0.65/kWh (Moner- Girona, et al., 2016) and Nigeria $0.35 (Adaramola , Paul, & Oyewola, 2014), additionally the design was competitive on a global level with other PV hybrid systems in Asia achieving $0.37/kWh in Thailand (Peerapong & Limmeechokchai, 2017). A sensitivity analysis was carried out using HOMER and showed how much the system components and diesel fuel costs affected the design and financial benefits, providing insight for further research.

With many diesel-fueled mini-grids scattered across Tanzania, a hybrid PV-diesel mini-grid is not just economically viable, but also offers a reduction in the levelised COE, presenting the opportunity for vast savings across Tanzania and significantly lowering harmful emissions whilst diversifying the energy mix. The potential to implement these changes across the country also presents better price negotiations for components, installation and maintenance due to the high demand as well as contributing to national employment of trained personnel in the renewables field. Considering the existing impacts of climate change, droughts experienced in Tanzania have significantly hindered hydropower generation and have highlighted another renewable energy source that waits to be exploited.

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