Techno-Economic Analysis of Hybrid Solar-Diesel Minigrids in Kenya: A Case Study of the Retrofitting Eldas Diesel Minigrid - Pilot Site

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Abstract

Generation of electricity from fossil fuels globally has led to the emission of greenhouse gases, which has been a major contributor of global warming. In addition, one of the biggest challenges in the developing world is the provision of reliable and affordable electricity access to remote and marginalized people where grid extension is too expensive.

Off-grid electrification program in Kenya for remote centres has been running since the early 80's. Until very recently, all sites were 100% powered by diesel generators. The Ministry of Energy is supporting the Rural Electrification and Renewable Energy Corporation and Kenya Power & Lighting Co. Ltd to hybridize 18 sites to maximize the use of renewable energy, reduce fuel costs and lower carbon emissions.

The government of Kenya spends up to 5 billion Ksh annually on diesel fuel for generators powering the remote sites namely (Mandera, Wajir, Kakuma, Merti, Habaswein, Elwak, Baragoi, Mfangano, Rhamu, Eldas, Takaba, Lokichoggio, Lokori, Laisamis, Faza, Kiunga, Hulugho, North Horr, Lokitaung, Dadaab, Maikona Lokiriama, Banisa).

A techno-economic analysis of retrofitting Eldas site shows that a 315.6 kW hybrid solar PV diesel hybrid system with four generators (2*65 kVA, 2*135 kVA) is sufficient to power the town of Eldas and its surroundings. Financial analysis shows that the payback period after retrofitting the minigrid is 9.5 years. In addition, 3,284 tons of Carbon

Dioxide is saved. Hybridizing all the sites shows that the government of Kenya will save up to 3 billion Kenya Shillings per year.

Key words: Solar PV-Diesel Minigrid, Payback Period, Greenhouse Gas Emissions,Techno-economic analysis, Eldas

1. Introduction

Over the years diesel generators in Kenya have been used to power households in off-grid rural setups and towns where the extension of the grid is prohibitively expensive. The use of diesel generators has been preferred due to their capability to supply power for 24 hours. However, the increased fuel prices and harmful carbon emissions have made the use of diesel generators only unattractive and expensive. Renewable energy systems on the other hand have been adapted due to the concerns of greenhouse gas emissions, which are contributing to climate change (Yamegueu et al. 2011).

The use of hybrid systems (diesel and solar and storage) is gaining popularity, because the use of solar energy is maximized during the day, the stored energy in batteries is maximized during the night and optimal-sized diesel generators are used to supply extra power that may be required during the peak and night hours hence ensuring reliable power. In addition, other benefits accrued include; adoption of renewable energy systems, reduction of fuel costs and reduction of carbon footprint.

To this effect, the Ministry of Energy in Kenya is supporting the Rural Electrification and Renewable Energy Corporation and Kenya Power & Lighting Co. Ltd to hybridize 18 sites. The ministry of energy spends about Ksh. 62.7 million on diesel fuel costs for Eldas power station and Ksh. 5 billion for all the 23 diesel powered mini grids in off grid areas on annual basis. In this paper, we focus on doing a techno-economic analysis of hybridizing the diesel minigrid site in Eldas, Wajir County.

Numerous authors have conducted techno-economic analysis in various parts of the (Asrari et al. 2012; Himri et al. 2008; Nema et al. 2009; Rehman and Al-Hadhrami 2010; Said and Ahmed 2014; Yamegueu et al. 2011), however, we have not come across any published work for Kenya on techno-economic analysis of hybridizing the diesel minigrid site in Eldas.

2. Methodology

1.1 The existing layout of Eldas hybrid minigrid

Eldas' power plant currently consists of one diesel generator operational since 2016, a 1*300kVA diesel generator, one 36kWp Solar PV power plant installed in August 2015 and one step-up transformer 1MVA 415V/33kV. The solar plant has not been operational for 2 years.

1.2 Solar radiation analysis from satellite data

The Global horizontal irradiance (GHI) and temperature for the Eldas area ranges from 5 kWh/m^2 to 6.3 kWh/m^2. Temperature ranges from 26.6 ^{0}C to 30.3 ^{0}C.

1.3 The daily energy demand profile

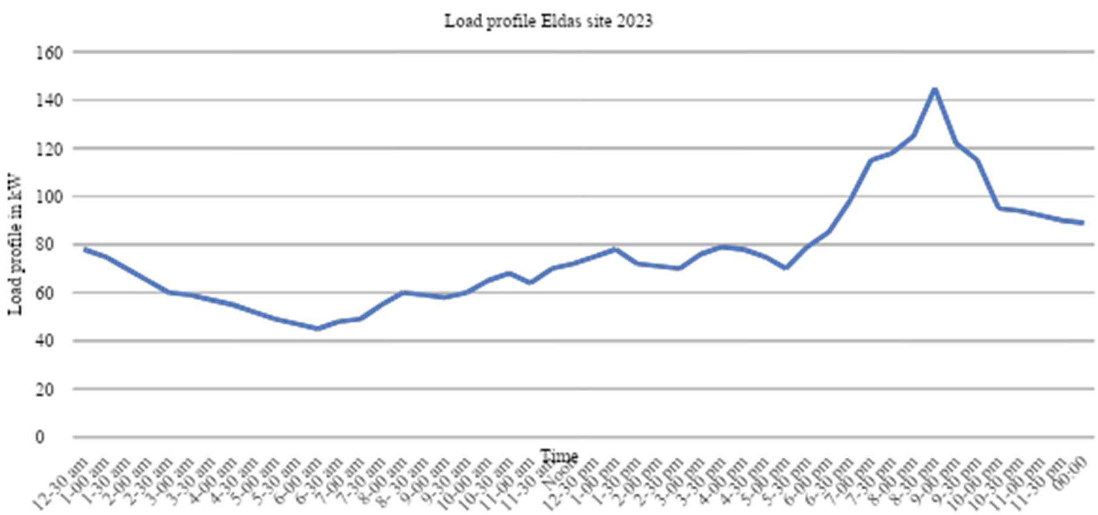

Fig 1: Daily energy demand profile at Eldas

The daily energy demand varies from a minimum of 45 kW during the day to a peak load of 145 kW at night as shown in Figure 1.

1.4 Hybrid minigrid sizing and simulation

Design and sizing was carried out as detailed below and verified by simulation using Homer software as shown in Table 1 and 2.

Table 1: Solar PV plant sizing

Peak load	2% yearly load increase in Zero year	6.5% yearly load increase	5% yearly load increase	22% (Losses factor)
145 kW	147.9 kW	202.6 kW	259 kW	315.5 kW

Table 2: Generator sizing

Peak load	2% yearly load increase in Zero year	6.5% yearly load increase	5% yearly load increase	30% (Losses)	1/6	1/6	1/3	1/3
145	147.9	202.6358175	259	336.2	56.03	56.0	112.1	112.1

The distribution of the nominal power of the diesel generators is calculated as follows (33%/33%/16.7%/16.7%) as shown in Equations 1 and 2; to allow for the flexibility of picking load step-wise as it increases. Therefore, power per genset (at prime power)

$$\frac{Pnorm}{6} = \frac{336}{6} = 56 \text{ kVA} \quad \text{with a +/- 20\% margin} \qquad (1)$$

$$\frac{Pnorm}{3} = \frac{336}{3} = 112\text{kVA with a +/- 20\% margin.} \qquad (2)$$

Thus, the total kVA prime rating is 400 kVA with the sizes are; generator 1 – 65kVA, generator 2 – 65kVA, generator 3 – 135kVA, and generator 4 – 135kVA

Table 3: Battery capacity calculation

Total daily energy kWh	Days of Autonomy	Battery efficiency	Depth of discharge	Battery capacity kWh
476	1	0.95	0.8	626.3

Table 3 shows the parameters used to calculate the battery capacity using the formula in Equation 3

$$\frac{Total\ daily\ energy\ demand * Days\ of\ Autonomy}{Battery\ efficiency * Depth\ of\ Discharg} = 626\ kWh \qquad (3)$$

Thus battery-rated capacity 260 Ah, Nominal voltage 44.8V, and energy 12.544 kWh was selected.

1.5 PV module, inverter, converter capacity calculation and selection

The PV panel selected is monocrystalline 540W and the parameters for the module at standard test conditions include; Open–circuit voltage (Voc) 49.6 V, Short-circuit current (Isc) 13.86 V, Operating voltage (Vmpp) 41.64 V and Operating current (Impp) 12.97 V. The DC-DC converters (model PDS1-400K) selected are modular in design and housed inside a cabinet that can hold up to 8 pieces of the modular converters. Each modular converter is rated at 50kW with an input current of (0-130 A) and an input voltage of

(250-800V). The cabinet is rated at 400kW. Therefore, the sizing of the PV array is as shown in Equation 4.

$$\text{No of panels} = \frac{315{,}900\ W}{540\ W} = 585\ \text{pcs} \quad (4)$$

The voltage and current of the PV string should be within limits of the 50 kW converter input current and voltage levels. One string comprises 15 panels with a Voc of 744 V as shown in Equation 5, while Equation 6 shows the Voc with a temperature correction factor of 1.02

$$V_{oc} = 49.6\ V \times \text{No. Of panels per string (15)} = 744V_{oc} \quad (5)$$

$$744V \times 1.02 = 758.88\ V_{oc} \quad (6)$$

$$585\ \text{panels}/15\ \text{panels per string} = 39\ \text{strings}$$

The string current (I_{sc}) is 13.86A and the number of strings per DC-DC combiner in use is 6. The maximum string array current per DC – DC combiner will therefore be:

$$= 13.86A \times 6 = 83.16A \quad (7)$$

$$\text{Peak power per converter} = 15\ \text{panels} \times 6\ \text{strings} \times 540W = 48{,}600W \quad (8)$$

$$39\ \text{strings}/6\ \text{strings per converter} = 6.5 = 7\ \text{converters of 50kW each} \quad (9)$$

1.6 Battery Inverter sizing

The loads supplied are AC in nature thus there is a need to use a battery inverter for converting DC output to alternating current (AC) therefore; six inverters of 62.5 kVA were selected for this hybrid plant. The cabinet holding 8 pieces of inverters is rated at 500kVA. The inverter is selected in such a way as to achieve an AC-to-DC ratio of 1.1 to 1.25.

$$= 6 \times 62.5 = 375\ \text{Kva} \quad (10)$$

$$\text{DC/AC ratio} = \frac{375\ kW}{315.6\ W} = 1.18 \quad (11)$$

The selected inverter model PWS1-500KTL-NA specifications include a nominal power of 500 kVA, battery voltage range of (600-900V), DC current of 837 A, AC voltage of 400 V, and AC current of 720 A. In addition, two isolation transformers are also provided each rated at 200kVA.

1.7 The Eldas hybrid Minigrid schematic/single line diagram and homer simulation extract

System Architecture

Component	Name	Size	Unit
Generator #1	GEN 1. 65 KVA / 52 kW	52.0	kW
Generator #2	GenGEN 2. 65 KVA / 52 kW	52.0	kW
Generator #3	GEN 3. 135 KVA / 108kW	108	kW
Generator #4	GEN 4. 135 KVA / 108kW (1)	108	kW
PV	Generic flat plate PV	316	kW
Storage	Generic 1kWh Li-Ion	640	strings
System converter	System Converter	375	kW
Dispatch strategy	HOMER Load Following		

Fig 2: Homer simulation extract

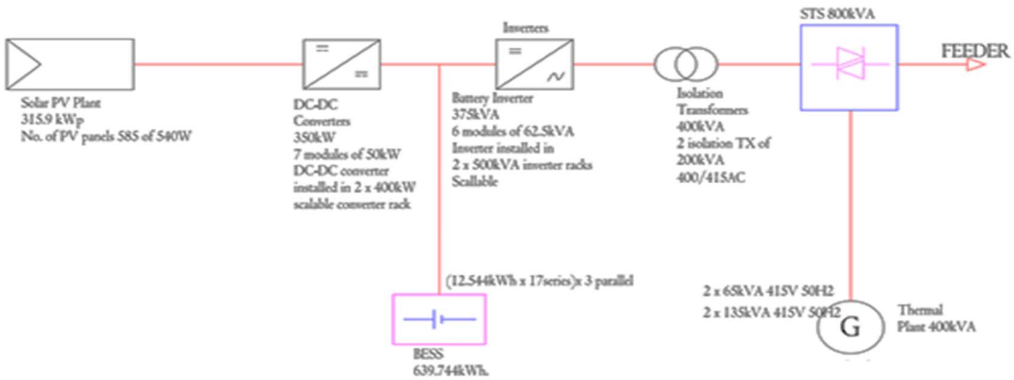

Fig 3:Eldas single line diagram

Figures 2 and 3 show the Homer simulation and Eldas single line diagram respectively

1.8 Economic feasibility to appraise the viability of the project

The overall project cost for the Eldas site is Ksh. 374, 151,594.5. The benefit accrued from the plant installed is the avoided cost of fuel. Ksh. 374,151,594.5 is spent annually on fuel for diesel generators at the Eldas site. Simulation through Homer shows that after installation 62% of the plant power supplying the loads will be from renewable energy. Therefore, the payback period can be calculated as follows

$$\text{Payback period} = \frac{Capital\ cost\ in\ Ksh}{(\ Avoided\ fraction\ of\ fuel\ cost\ in\ Ksh\ on\ an\ annual\ basis)} \quad (12)$$

The total amount of money spent by the government on fuel for the 23 diesel-powered sites is Ksh. 5,273,180,524.20. Equation 13 shows the estimation of the fuel cost savings. With the installation of the solar PV diesel plant in all 23 diesel-powered sites, the fuel consumption will be reduced by 62%.

Annual fuel cost for all the diesel-powered plants in Ksh x Renewable energy fraction (13)

1.9 Carbon Balance calculation

The carbon balance is calculated using the energy yield of the PV installation for one year as computed by the PVsyst simulation, the system lifetime of 25 years, the grid LCE given in gCO_2/kWh and PV system LCE, given in tonnes of CO_2 (the total amount of CO_2 emissions caused by the operation and construction of the PV installation) as shown in Figure 4.

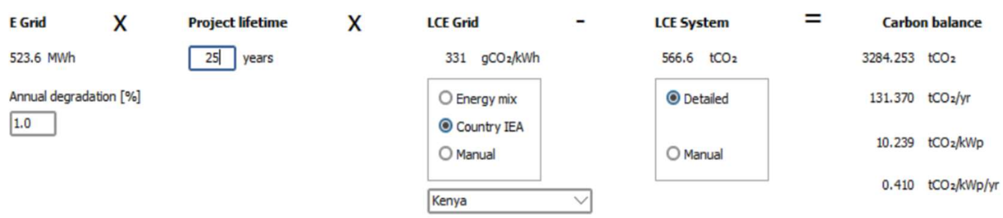

Fig 4: Carbon balance calculation

3. Results

Figure 5 shows an extract of the simulation from Homer. The total yearly production from solar PV is 511,712 kWh/yr, accounting for 62% of total generation. On the other hand, the annual generation from diesel generators is 317, 711 kWh/year which accounts for 38% of total generation.

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	511,712	61.7
GEN 1. 65 KVA / 52 kW	141,050	17.0
GenGEN 2. 65 KVA / 52 kW	103,223	12.4
GEN 3. 135 KVA / 108kW	73,429	8.85
GEN 4. 135 KVA / 108kW (1)	0	0
Total	829,414	100

Fig 5: Homer simulation extract

Economic analysis of hybridizing Eldas power plant shows that the payback period is 9.5 years as shown in equation 14. In addition, hybridizing all the sites shows that 3.3 billion shillings will be saved by the Kenan Government as shown in equation 15.

Payback period = $(Ksh. 374{,}151{,}594.5)/\ (62{,}745{,}216.00 * .62\ )$ = 9.5 years (14)

Ksh. 5,273,180,524.20 x 0.62 (renewable energy fraction) = 3,269,371,925 (15)

4. Discussion

Design and simulation of the solar PV plant using Homer shows that a 315.6Wp solar PV, 400 kVA diesel generator set (65, 65, 135, 135) kVA, battery storage of 640 kWh will be sufficient to provide reliable power for the town of Eldas (for current loads and future loads).

Economic analysis shows that the payback period of hybridizing the plant is 9.5 years which is favorable as it is less than the lifetime of the solar-diesel hybrid plant. Hybridizing all the sites shows that 3.3 billion shillings will be saved which the government can channel to more useful areas of need. In addition, a carbon balance of 3284 tons of CO_2 is achieved. Diversified sources of energy to constitute the hybrid plant will also ensure reliable power at all times for the residents of Eldas and its environs.

5. Conclusions

In this work, we carried out a techno-economic analysis of hybridizing the Eldas site. Design and sizing was carried out and verified using Homer software. Economic analysis was also done to determine the payback period of hybridizing the Eldas site and the carbon balance was calculated. Therefore, this work shows that 315.6Wp solar PV, 400 kVA diesel generator set (65, 65, 135, 135) kVA, battery storage of 640 kWh will be sufficient to provide reliable power for the town of Eldas (for current loads and future loads).

In addition, the payback of the project is 9.5 years. Hybridizing all the diesel-powered sites also shows that the government of Kenya will save 3.3 billion shillings annually. A carbon balance of 3284 tons of CO_2 is also realized. Thus, the techno-economic analysis of hybridizing Eldas site shows that it is technically and financially viable.

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