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Applying grid-connected photovoltaic system as alternative source of electricity to supplement hydro power instead of using diesel in Uganda

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ABSTRACT

Uganda's electricity sector for long has been depending on hydro as a base power source. Diesel is currently the second source of electricity which supplements the hydro power. The use of diesel has some implications; first, the price of fuel is high and therefore the energy produced is also expensive. Secondly, diesel power would not be a better option because of its immediate and long term effect on environment due to carbon emission and other pollutants that are often injected into atmosphere from diesel. This paper therefore examines the possibility of using solar PV systems as alternative to diesel as a source of electricity. The paper has also established that the tendency of depending on non-renewable sources of electricity can be minimized and at the same time reducing the cost of energy in the future.

1. Introduction

The economy of Uganda is endowed with natural resources that support the development of its power industrial sector. The connection of the country to river Nile assures a good atmosphere for the construction of hydro electric power stations [1]. However, hydro power, as a base source, necessitates supplementary forms of power source. The construction of the two diesel power stations (Kiira Nalubale Aggreko and Mutundwe thermal power stations) and Namanve thermal power yet to be commissioned are such efforts made to supplement hydro power [2]. Diesel power would not be the better option because of its immediate and long term effect on environment due to carbon emissions and other pollutants that are injected into atmosphere from diesel. Therefore, a supplementary power source can be employed which may supply additional power as well as ensuring sustainability and a healthy environment. It is therefore necessary to carry out a study to find out the best alternative to diesel as a source of electricity such as solar photovoltaic (PV) systems.

Uganda is endowed with plenty of sunshine giving solar radiation of about 4–5 kWh/m^2/day [3]. This level of radiation is quite favourable for all solar technology applications. The work of the authors in [4] includes extensive studies of solar energy applications by using advanced simulation tools. The study on the performance of a 268Wp stand-alone PV system test facility was carried out on a 268Wp stand-alone PV test facility installed at the University of Ghana at a maximum solar irradiance of 1.05 W/m^2 for March and 0.85 Wm^2 during January 1988 [5].

It is well known that PV connected systems are quite expensive to finance especially at the initial stages of implementation and without subsidies, the economies of the solar power are doubtful. Though Uganda's economy is currently supported by donor funds [6], with the discovery of oil in the Eastern part of the country, Uganda is likely to enhance its financial base which is an important ingredient in the building of the national economy. Hence, the designed PV systems are expected to have financial support if they are incorporated into the national future power plan. The implementation can be done in different ways. First, through the government, by subsiding the potential solar power producers to generate solar power for example since 2001, the Netherlands had a new subsidy programme for PV projects in order to increase the implementation of PV systems on house [7]. Another way is to implement the installation of PV systems through independent power producers who may be paid by government through long term purchasing agreements.

Solar energy has been pursued by a number of countries with a monthly average daily solar radiation in the range of 3–6 kWh/m^2

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in an effort to reduce their dependence on fossil fuels [8]. Solar energy applications in Uganda include household solar photovoltaic (PV), water heating, cooling and crop drying. Given the shortfall in energy supply and the world's call to utilise the renewable energy in respect to environmental concerns, there is need to supplement Uganda's energy supply with solar systems; stand-alone PV for those areas that are far away from the grid whereas grid-connected PV systems can be placed in areas which already have access to the grid.

Many researchers have presented papers about the study on the design and implementation of grid-connected PV solar systems [9]. A successful implementation of a grid-connected solar PV project is a 200 kWp grid-connected PV system at Jae'n University campus in Spain. It comprises of the installation of four PV sub-generators connected to a low voltage grid at Jae'n University campus with a total cost of 1,513,158 Euros excluding cost of demonstration phase. The study was carried out on small solar PV generators that examined the engineering, commercial and regulatory aspects of the grid-connection of small PV systems in the UK, and compared the situation with other European countries where several thousand systems are being installed under either sponsored or independent programmes [10]. Carbone (2009) discussed the different interesting ways that can be followed in order to reduce costs of PV systems [11]. The use of energy storage in PV plants was introduced, discussed and tested by experimental measurements. A computer software application was developed to simulate hourly energy flow of a grid-connected photovoltaic system [12]. This software application enables conducting an operational evaluation of a studied photovoltaic system in terms of energy exchange with the electrical grid. However, there is lack of emphasis on the concept of net metering plan.

Mohamed A. E and Zhao investigated and emphasized the importance of the PV system regarding the intermittent nature of renewable generation, and the characterization of PV generation with regard to grid code compliance [13]. The investigation was conducted to critically review the literature on expected potential problems associated with high penetration levels and islanding prevention methods of grid tied PV.

This paper therefore is intended to present a design of a grid-connected solar PV system for Uganda using HOMER energy software tool. Cape & Islands Self-reliance [14] has prepared a guide document that outlines the fundamental operation of a PV system, identify its components, and describe the way it works. This design consists of a PV array (PV modules) with electronic control system, an inverter module, a battery bank, DC link and AC link for connecting the output power to the load and the grid.

The HOMER energy modelling software is a powerful tool for designing and analyzing hybrid power systems, which contain a mix of conventional generators, cogeneration, wind turbines, solar PV, hydro power, batteries, fuel cells, hydro power, biomass and other inputs. It is currently used all over the world by tens of thousands of people [15]. This software has been applied for research in many simulations. A techno-economic feasibility analysis was done for 500 kW grid-connected solar PV system using HOMER software and RET Screen computer tools [16]. The potential of solar PV system in Bangladesh was estimated utilizing Geo-Spatial toolkit, NASA SSE solar radiation data and HOMER optimization software [17]. Excel modelling tool would be used for analysis but has some limitations. An economic evaluation of photovoltaic grid-connected systems (PVGCS) for companies situated in Flanders (Belgium) was conducted by using a generic Excel model [18]. However, excel is lacking built in system components such as inverters, PV array and others that can be used in the simulation of the system, hence the visibility of using HOMER software tool.

2. Background information

2.1. Load profile

In this study, a remote residential area was selected as a case study and the load profile was generated based on various factors. The design of the system was based on a selected area in Masaka, one of the districts in Uganda whose coordinates were obtained. The area was assumed to have 35 homes with a maximum load demand of 1.3 kW/day/household. It was assumed that the daily load demand varies seasonally throughout the year with a maximum of about 46 kW peak demand. The daily load profile of the area is shown in Fig. 1.

People depend mainly on subsistence farming and spend most of their day in gardens. Therefore the load varies slightly during day time with a maximum demand during evening hours. At 6 am, people wake up to go for gardening whereas others remain in small towns doing some daily income activities such as attending small shops and operating restaurants. Most of the power during this time is consumed by low power residential household appliances such as lighting and televisions. At mid night, the electricity consumption becomes very low as most people go to sleep with small number of security lightings.

The load demand further varies monthly with August, September and December seasons having higher demand. These periods are characterised by large amount of rainfall especially during morning hours which prevent people from going to their farms and gardens and therefore they spend much of the day listening to news and music on radio cassettes. The monthly load profile is shown in Fig. 2. A random variability factor of 1.97% for day-to-day and 1.94% for time-step-to-time-step was given to HOMER software to cater for differences which may occur each day in load profile and the energy demand requirement for a year was generated automatically by HOMER software.

2.2. Solar radiation and clearness index

The solar radiation was generated automatically with HOMER by inserting the coordinates (longitude and latitude of 0 22′ S and 31 46′ E, respectively) of the selected area [19]. Fig. 3 shows the daily radiation and clearness index for every month of a year generated in the software. The maximum radiation is about 3.35 kWh/m^3/d which is enough to generate the required power for the area.

2.3. Energy purchase price and feed-intariff

The load considered in the area is domestic in nature. The tariff of electricity for domestic consumers in Uganda (fixed rate) is 385.6UGX/kWh which is equal to US dollar of $0.171/kWh (For $1 equal to 2250UGX as of 2010). The "feed-in-tariff" or sellback price for renewable energy less than 20 MW in Uganda has multiple rates which are $0.12/kWh for peak (1800–2400 hrs), $0.064/kWh for

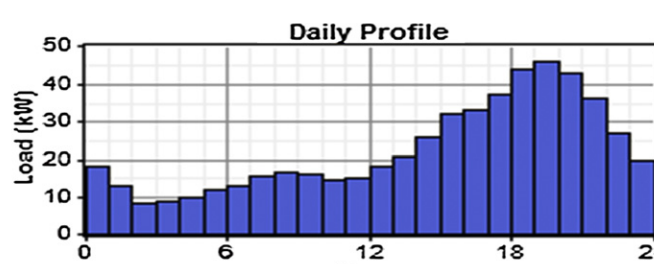


Fig. 1. Daily load profile of Masaka.

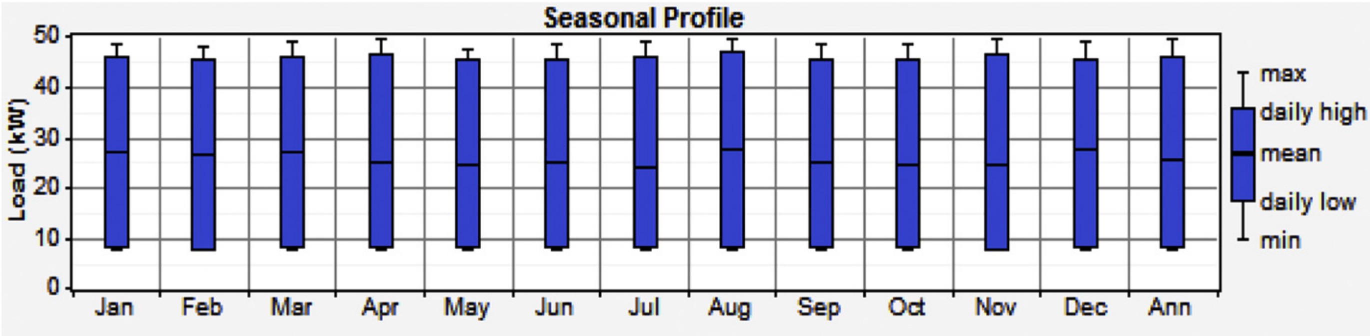


Fig. 2. Monthly load profile.

shoulder (0600–1800 hrs) and \$0.04/kWh for off-peak (0000–0600 hrs) [20]. The sellback rates are for year one until year six and beyond six years the rates differ. However, during optimization process in HOMER, the rates were used until 25 years; the lifetime of the designed system. This is because HOMER doesn't have the feature to include multiple rates for different periods of the year. Fig. 4 shows the purchase and sellback rates that were fed in HOMER. The feed-in-prices considered are 0.120, 0.064 and 0.04USD for the peak, shoulder and off-peak hours respectively. Fig. 4 further shows the schedule of these periods throughout the day. These periods (peak, shoulder and off-peak) were considered to be constant throughout the year for simplicity of the analysis.

3. Design layout

3.1. Description of the system

The design layout consists of several blocks including the PV array (PV module), energy storage device (battery bank), converter (inverter) and system output (grid and the load) as shown in Fig. 5. The PV array, battery bank and inverter were analysed critically for their specifications whereas for the grid, the data was obtained from available utility data. The output of the converter which is connected to AC link is 3-phase 415VAC. The load is based on consumers' choice where by consumers can connect to AC link in single or three-phase. The connection to the utility grid from AC link is also in 3-Phase. The dotted and solid lines represent DC and AC connections respectively. The two-way arrows indicate that the power can flow in both directions.

The function of the PV array is to extract solar energy from the sun and convert it to DC voltage. The generated voltage is converted to AC by the inverter. The Battery bank is only charged by the excess electricity from PV array after fully supplying the load. This is called load following strategy. The battery bank is used to top up the low power output of PV array during low radiation. During the night where there is no solar radiation, the grid will totally supply the load. In net metering scheme, the surplus energy by PV array will be sold back to the grid using "feed-in-tariff" determined by the utility. The net supply electricity to the grid (S_N) is equal to the electricity supplied to the grid (S_{GD}) minus electricity supplied by the grid (S_{GN}) as in Eq. (1).

$$S_N = S_{GD} - S_{GN} \quad (1)$$

In the design layout, the metre for net metering is not included because it does not affect the output power to be generated from this power system design. However, in HOMER software, the sell-back price or feed-in-tariffs were included in order to determine the best reduction in annual payment price to the grid.

4. Design specifications and costs

4.1. PV array

The designed PV is rated 100 kW and this is the base electricity supply for the system. Part of this power can be used to satisfy the load demand of the chosen area as well as supplying the excess to the grid. The designed PV array has 2000 modules with each proposed module rated at 50 W, with a nominal voltage of 12 V. The

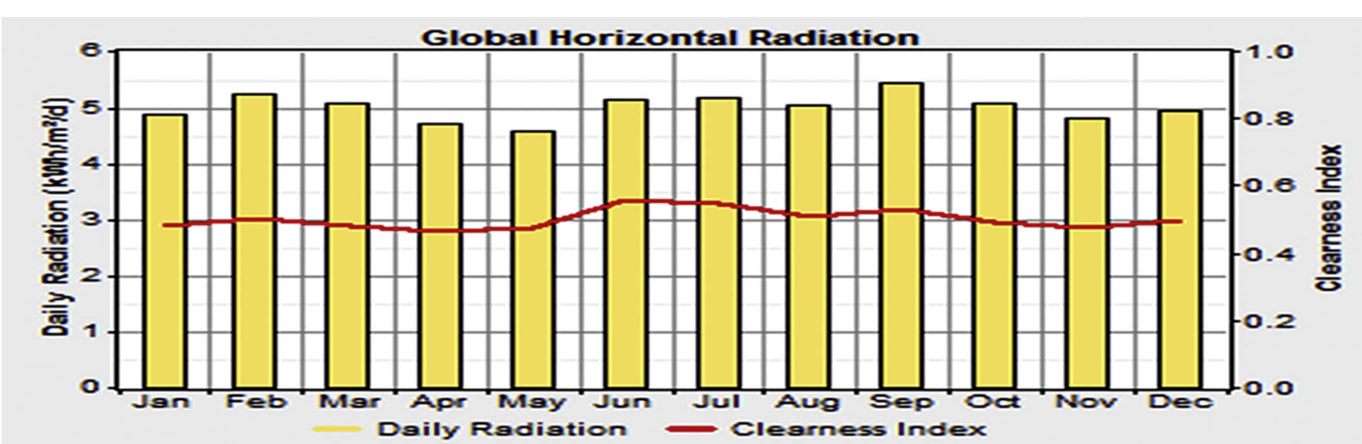


Fig. 3. Daily radiation and clearness index.

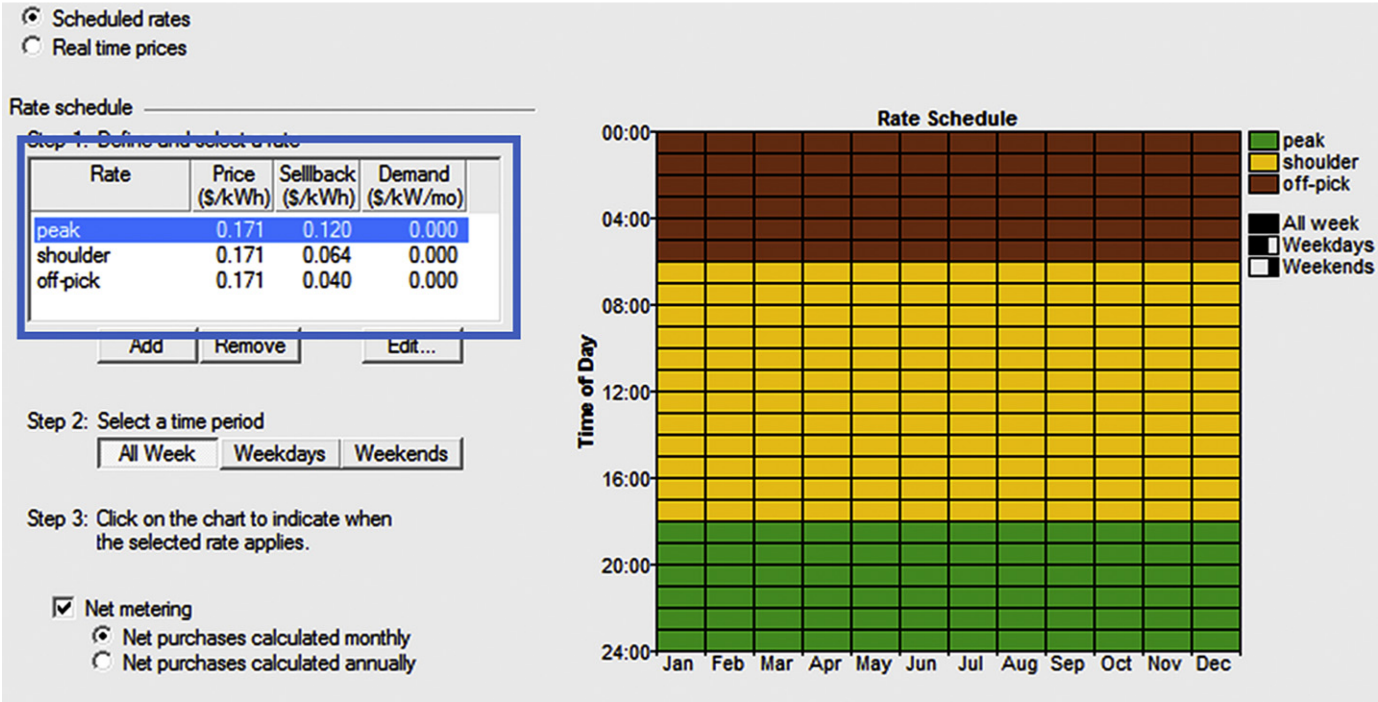


Fig. 4. Purchase and sellback price.

area for each module is 0.871 m^2. The total area that can be occupied by all the modules is 774.192 m^2.

The cost for a 50 W PV module was assumed to be $300. So, the initial cost of PV will be $6000/kW based on the cost of each of the 20 proposed PV modules of 50 W that make a total of 1 kW. The replacement cost for a 50 W PV module was assumed to be $250. This is equal to $5000/kW. Operating and maintenance cost was assumed to be $1200/year or $100/month for either technical or social (security of the equipment) factors. The lifetime for PV array is 25 years.

4.2. Converter

The inverter is rated at 100 kW AC output power based on 100 kW DC input power from PV array. The output of the inverter is 3-phase 415VAC 50/60 Hz. The capital cost of inverter was assumed to be $42,900 ($429/kW). The operating and maintenance cost was assumed to be zero. The efficiency of the inverter is 95.5% and the lifetime is 16 years which means that the inverter has to be replaced once in 25 years period of PV array lifetime. The replacement cost of inverter was assumed to be $40,000 ($400/kW). The inverter plays a vital role in the operation of the grid-connected PV system. The inverter selected for the power system should have features that make the system more robust. Proper control systems must be provided to the designated system such as the use of multilevel converter control schemes applicable to a general multilevel converter and to any types of the renewable energy resources [21].

4.3. Battery bank

The type of battery used is Surette 6CS25P [22]. The nominal voltage of the battery is 6 V and the nominal capacity is 1156 Ah. To have 12 V output, 2 batteries will be connected in series per string. When the radiation is low or the PV array is experiencing a shadow condition, the battery bank is capable of discharging for about 1 h. The minimum state of charge is 40% and the round trip efficiency is 80%. The capital and replacement cost were assumed to be $1200/battery and $1000/battery respectively. The operating and maintenance cost was assumed to be $10/battery/year. HOMER has the capability to do the sensitivity analysis of how many strings (0, 2, 4 or 6) will give the best optimization. From the optimization results, the best configuration in term of operating cost and total Net Present Value (NPC) was selected.

Table 1 gives an outline of the specification for each of the component in the design reflecting both technical and cost considerations.

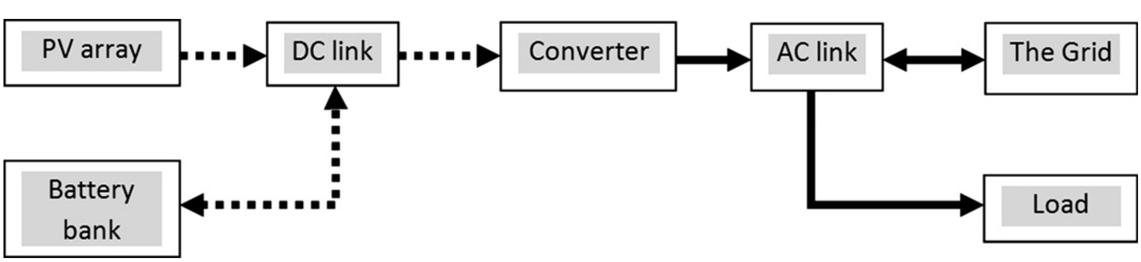


Fig. 5. Grid-connected solar PV system design layout.

5. System configuration

Fig. 6 shows the design of the grid-connected PV system as it was modelled using HOMER. Typically, PV panels are mounted at fixed orientation. However they can be made to “track” the sun in order to maximize the incident solar radiation and HOMER has the feature to include PV tracking.

6. Results and discussions

The purpose of the renewable energy system is to reduce the use of fuel in generating electricity in conventional power plants such as diesel and coal power plants. There has been increased use of fuel especially diesel and petrol in the previous decades due to industrialisation and transportation. This is projected to result into exhaustion of these resources and increase their prices further in addition to the hazardous production of carbon wastes. The increasing use of renewable energy supply will contribute to safe fuel usage, reduce emissions caused by fuel burning and hence reduce the cost of energy. By connecting a lot of distributed energy system such as PV and other types of renewable energies to the grid, the electric tariffs in the future are likely to reduce. Even though the capital cost of renewable energy system is still very high, the feasibility to have cheaper cost of energy in the future can be met by increasing the penetration of renewable energy such as PV generator.

The simulation was performed by comparing grid-connected PV without and with energy storage (battery bank) for a project lifetime of 25 years with 4.8% annual interest rate. The calculation of annual interest rate was done using formula in Eq. (2).

$$i = \frac{i' - f}{1 - f} \tag{2}$$

Where

i = real interest rate
i' = nominal interest rate (the rate at which the loan could be secured)
f = annual inflation rate

Table 1
Specification details for each component in the design.

Component	Specification	Description
PV array	Size	100 kW
	Capital cost	\$6000/kW (20 × \$300/50 W)
	Replacement cost	\$5000/kW (20 × \$250/50 W)
	O&M costs	\$1200/year
	Lifetime	25 years
Converter	Size	100 kW
	Type	3-phase
	Capital cost	\$429/kW
	Grid voltage & frequency	415VAC 50/60 Hz
	O $ M cost	\$0/year
	Lifetime	16 years
	Efficiency	95.5%
Battery	Type	Surrette 6CS25P
	Nominal voltage	6 V (12 V for 2 batteries per string)
	Nominal capacity	1156 Ah
	Minimum state of charge	40%
	Round trip efficiency	80%
	Nominal energy capacity of each battery	6.94 kW
	Capital cost	\$1200
	Replacement cost	\$1000
	O $ M cost	\$10/year

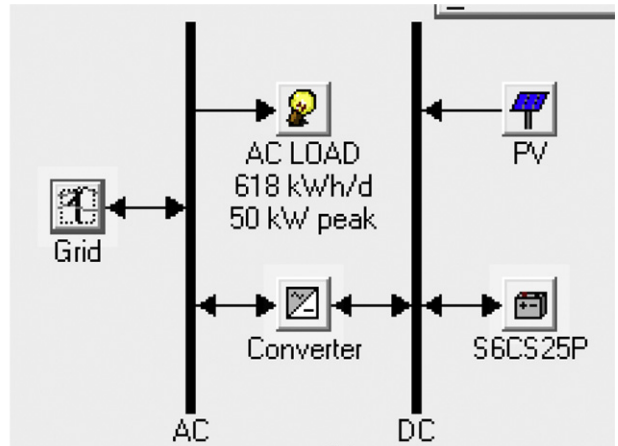


Fig. 6. System configuration.

By using current information for Uganda where nominal interest rate is 18% and inflation rate is 12.6% (for 2010) [23], the real interest rate calculated was 4.8%.

6.1. HOMER optimization

The battery storage was varied between 0, 4, 8 and 12 units for comparison purpose (2 units per string). Zero units’ means no battery was considered. This was done using sensitivity analysis inside HOMER. The result of HOMER optimization is shown in Fig. 7.

From HOMER optimization, the analysis was carried out for two components only; a 100 kW PV and an inverter. This is because the selected 100 kW PV and inverter were considered for their specific cost such as initial capital, replacement and maintenance cost. To determine the optimum combination of PV and inverter, multiple cost values (in US\$) of these components were entered in sensitivity values for the selected options and HOMER gave multiple results from which the best pair was determined. For this analysis, only 100 kW PV and 100 kW inverter were considered because of the assumption that, in the future when the load is increasing with time, 100 kW specification is far enough to cater for the load (currently peak demand is 45.5 kW) and this would save the cost related to the extension of PV and/or upgrading inverter in the future. Such a system can be implanted in similar areas as the case study areas in Uganda to serve power for such a long time of 25 years with minimum dependence on the variable costs involved in conventional power systems for example the cost of replacing the damaged transformers and the cost for paying maintenance engineers.

6.2. Analysis of energy supply without any renewable energy system

From Fig. 8, it can be observed that the cheapest configuration option is to use the supply from the grid only without any PV generator with a total Net Present Cost (NPC) of \$554,706. This configuration also has the cheapest cost of energy (COE) of \$0.171/kWh. The operating cost is \$38,573/year. The operating cost was calculated by multiplying total energy purchased (225,570 kWh/year) with the purchase price of \$0.171/kWh. The initial capital is totally zero because there is no need for installation of PV generator, inverter and energy storage system.

From Fig. 8, the total NPC of the grid only configuration came from the grid since the grid was the only supply to the load. Fig. 9 shows that total energy of 225,570 kWh/year was purchased from the grid and no fraction of supply is coming from PV. It can be

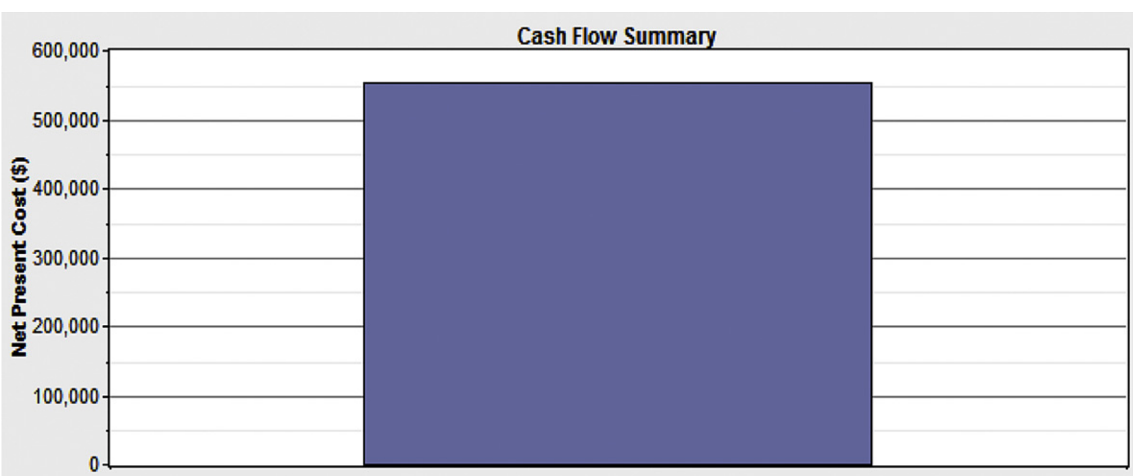
Double click on a system below for simulation results.

PV (kW)	S6CS25P	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
			500	$ 0	38,573	$ 554,706	0.171	0.00
	4	80	500	$ 39,120	39,529	$ 607,585	0.187	0.00
	8	80	500	$ 43,920	39,737	$ 615,367	0.190	0.00
	4	100	500	$ 47,700	39,717	$ 618,860	0.191	0.00
	12	80	500	$ 48,720	39,944	$ 623,149	0.192	0.00
	8	100	500	$ 52,500	39,924	$ 626,641	0.193	0.00
	12	100	500	$ 57,300	40,131	$ 634,423	0.196	0.00
80		80	500	$ 514,320	20,241	$ 805,397	0.248	0.47
80	4	80	500	$ 519,120	20,494	$ 813,843	0.251	0.47
80		100	500	$ 522,900	20,428	$ 816,671	0.252	0.47
80	8	80	500	$ 523,920	20,744	$ 822,235	0.253	0.48
80	4	100	500	$ 527,700	20,681	$ 825,117	0.254	0.47
80	12	80	500	$ 528,720	20,989	$ 830,562	0.256	0.48
80	8	100	500	$ 532,500	20,931	$ 833,510	0.257	0.48
80	12	100	500	$ 537,300	21,177	$ 841,836	0.260	0.48
100		80	500	$ 634,320	17,575	$ 887,063	0.273	0.54
100	4	80	500	$ 639,120	17,779	$ 894,796	0.276	0.54
100		100	500	$ 642,900	17,717	$ 897,692	0.277	0.54
100	8	80	500	$ 643,920	17,969	$ 902,334	0.278	0.55
100	4	100	500	$ 647,700	17,930	$ 905,543	0.279	0.54
100	12	80	500	$ 648,720	18,136	$ 909,534	0.280	0.55
100	8	100	500	$ 652,500	18,127	$ 913,184	0.282	0.55
100	12	100	500	$ 657,300	18,300	$ 920,472	0.284	0.55

Fig. 7. Overall HOMER optimization results.

noticed that the monthly average electric production matches the monthly load profile where there are slight reduction of the load and energy production between April to July and September to November.

Even though this configuration has the lowest NPC, but as mentioned earlier, the objective of introducing solar PV is to reduce adverse effect of the generated pollutants from the diesel power systems as well as reducing the cost of energy in the future. So, this



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Grid	0	0	554,706	0	0	554,706
System	0	0	554,706	0	0	554,706

Fig. 8. Cash flow summary.

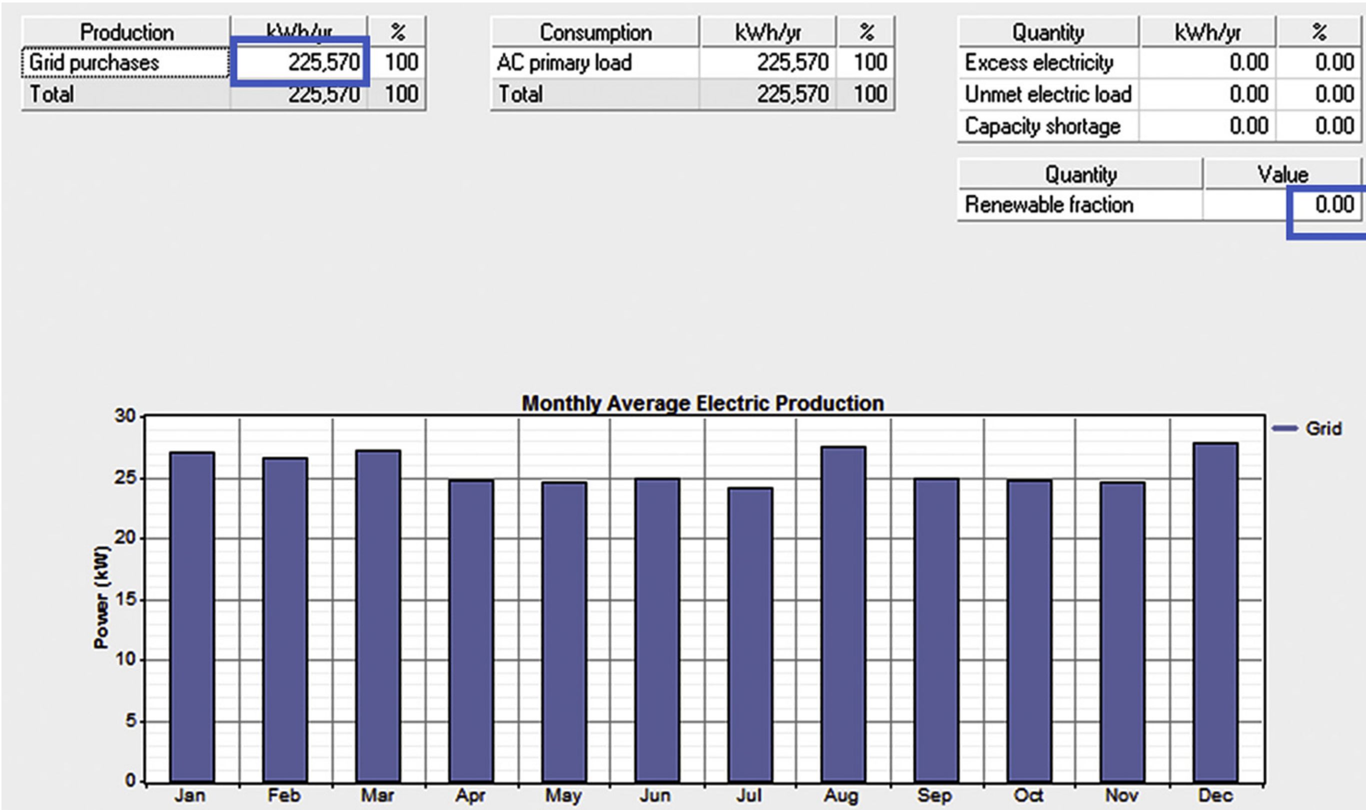


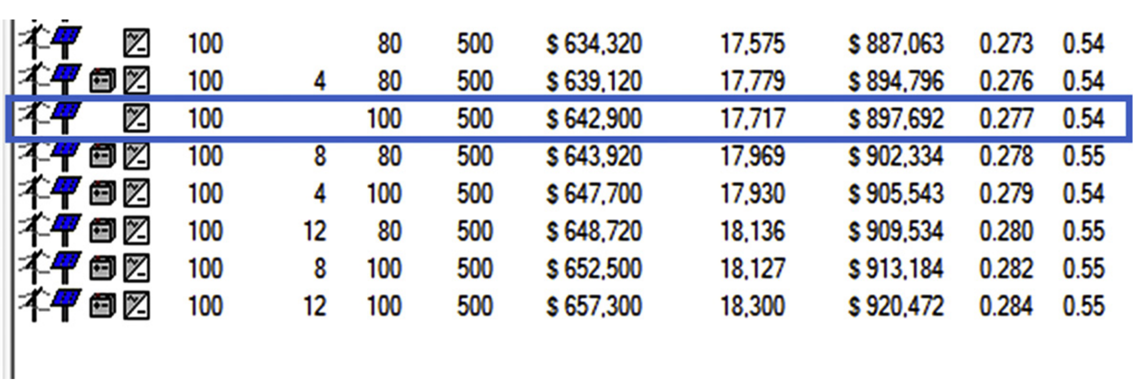
Fig. 9. Monthly average electric production.

type of configuration is not considered as an optimal solution since it is not likely to reduce the dependency on diesel.

6.3. *Analysis-grid-connected PV without energy storage*

From the optimization results of Fig. 10 for the grid-connected PV without energy storage, the total NPC is $897,692 while the operating cost is $17,717/year. The initial capital is $642,900 and the cost of energy is $0.277/kWh. Compared with the configuration of grid only, this configuration has higher initial capital and total NPC. This is because the total NPC includes the initial capital and replacement cost of inverter, initial capital of PV and operation and maintenance (O&M) cost. Zero replacement cost was considered for PV generator because its lifetime is 25 years, which is the project period. On the other hand, inverter has 16 years lifetime which means that it has to be replaced once in 25 years time. In the simulation, the O&M cost of inverter was assumed to be zero because the inverter selected is of good design made of reliable electronic components which do not need to be replaced frequently. It can be noticed that the operating cost of the grid with PV has reduces to half the operating cost for configuration of grid only. This is because some amount of energy (surplus) in excess of the load requirement is sold back to the grid during day time when the PV is generating more power due to greater amount of solar radiation. This justifies the ability of the solar system to reduce the cost of energy in the future.

Even though the consumers have to pay higher for the COE per kWh ($0.277/kWh) compared to configuration of grid only ($0.171/kWh), the results of Fig. 11 show that this configuration has supplied a total 155,707 kWh/year from PV which is equivalent to a renewable energy penetration rate of 54% out of the total energy supply to the load. If this configuration is compared with the grid



100		80	500	$ 634,320	17,575	$ 887,063	0.273	0.54
100	4	80	500	$ 639,120	17,779	$ 894,796	0.276	0.54
100		100	500	$ 642,900	17,717	$ 897,692	0.277	0.54
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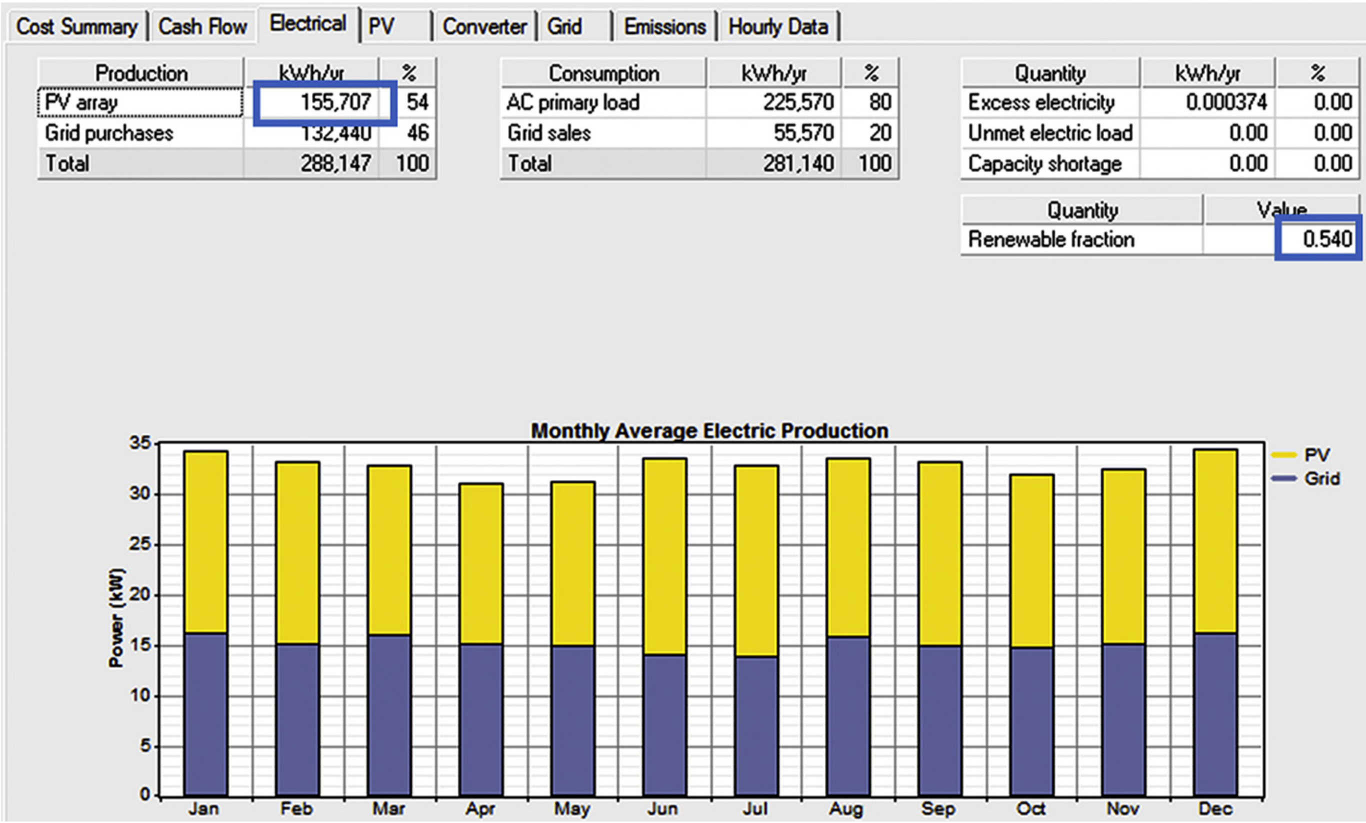
100	12	100	500	$ 657,300	18,300	$ 920,472	0.284	0.55

Fig. 10. Cost of grid-connected PV without energy storage.



Production	kWh/yr	%
PV array	155,707	54
Grid purchases	132,440	46
Total	288,147	100

Consumption	kWh/yr	%
AC primary load	225,570	80
Grid sales	55,570	20
Total	281,140	100

Quantity	kWh/yr	%
Excess electricity	0.000374	0.00
Unmet electric load	0.00	0.00
Capacity shortage	0.00	0.00

Quantity	Value
Renewable fraction	0.540

Fig. 11. Monthly average electric production.

only setting which contributes 100%, the results is that this system contributes the biggest share of clean/renewable energy implying that this is likely to reduce on the percentage of fuels which are injected to run diesel generators. Another advantage is the reduction on the amount of carbon emissions produced from diesel which comes with the reduction on the atmospheric pollution. The role of the government should be to introduce laws and policies that support renewable energy based systems which have potential to reduce the dependence on conventional energy sources like diesel. For instance China's Renewable Energy Law which took effect in 2006 has identified the key role of the renewable energy as "increasing energy supply, improving energy structure, guaranteeing energy safety, protecting environment and realizing the sustainable development of economy and society" [24].

In the long run, the COE would be further reduced if such small renewable energy systems are implemented to further reduce the amount of expensive fuels being used today to produce electricity. The electricity purchase tariffs are likely to reduce and the reality to have cheaper energy would become true.

Fig. 12 shows the energy purchased from the grid and sold back to the grid for every month. The net energy purchased by the grid from the PV is calculated by the formula given in Eq. (1). It can be observed from Fig. 12 that the PV contributes a reasonable amount of power to the national grid annually (76,870 kWh). If such small

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchases (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
Jan	12,031	4,678	7,353	48	1,380	0
Feb	10,109	3,822	6,286	44	1,207	0
Mar	11,829	3,703	8,126	46	1,432	0
Apr	10,841	3,958	6,883	46	1,323	0
May	11,067	4,413	6,654	46	1,322	0
Jun	10,094	5,629	4,464	47	1,153	0
Jul	10,242	5,889	4,353	45	1,175	0
Aug	11,742	3,921	7,820	48	1,408	0
Sep	10,744	5,375	5,369	46	1,229	0
Oct	10,892	4,772	6,121	46	1,301	0
Nov	10,886	5,064	5,823	47	1,243	0
Dec	11,962	4,344	7,619	49	1,408	0
Annual	132,440	55,570	76,870	49	15,581	0

Fig. 12. Monthly purchased and sold energy.

100		80	500	$ 634,320	17,575	$ 887,063	0.273	0.54
100	4	80	500	$ 639,120	17,779	$ 894,796	0.276	0.54
100		100	500	$ 642,900	17,717	$ 897,692	0.277	0.54
100	8	80	500	$ 643,920	17,969	$ 902,334	0.278	0.55
100	4	100	500	$ 647,700	17,930	$ 905,543	0.279	0.54
100	12	80	500	$ 648,720	18,136	$ 909,534	0.280	0.55
100	8	100	500	$ 652,500	18,127	$ 913,184	0.282	0.55
100	12	100	500	$ 657,300	18,300	$ 920,472	0.284	0.55

Fig. 13. Cost of grid-connected PV with energy storage.

grid-connected PV systems are installed throughout similar regions of the country, the shortage of power is likely to be reduced thereby reducing the price due to the force between supply and demand.

6.4. Analysis-grid-connected PV with energy storage

The function of energy storage is to store excess energy from renewable energy generator and to act as backup energy when the output of the PV generator becomes low when it is subjected to low solar radiation. This will optimize the system and reduces the cost in long run. The type of battery used is Surette 6CS25P. However, a number of alternative strategies can be considered in this case. First, the load following dispatch strategy was used in the simulation to charge the battery which means that the battery will only be charged by the surplus energy from the PV generator after fulfilling the load demand requirement. Secondly, the number of cycles of the battery used is about 2800 and the full charge of the battery is required in between the cycles. The batteries need to charge between every low discharge in an operation mode instead of load following strategy.

From optimization result as shown in Fig. 13 for the grid-connected PV with energy storage (100 kW PV generator and 100 kW inverter specification), the higher the number of batteries used, the higher the total cost. So, grid-connected PV with 4 batteries has the lowest cost for 100 kW specification. The initial capital for this configuration is $647,700 and the operating cost is $17,930/year. The NPC is $905,543 and COE is $0.279/kWh. It can be noticed that this configuration has slightly higher initial capital, operating cost, NPC and COE compared with configuration without energy storage. This setting can be implemented to explore the advantages of using backup energy such as reliability, safety of data in case if computers and other intelligent electronic equipments are connected on the system. Other inverter topologies can also be included to incorporate an uninterruptible power supply (UPS) in the system to serve other advantages like power factor correction and to reduce the effect of harmonics. However, this development comes with an increase in the cost of the project.

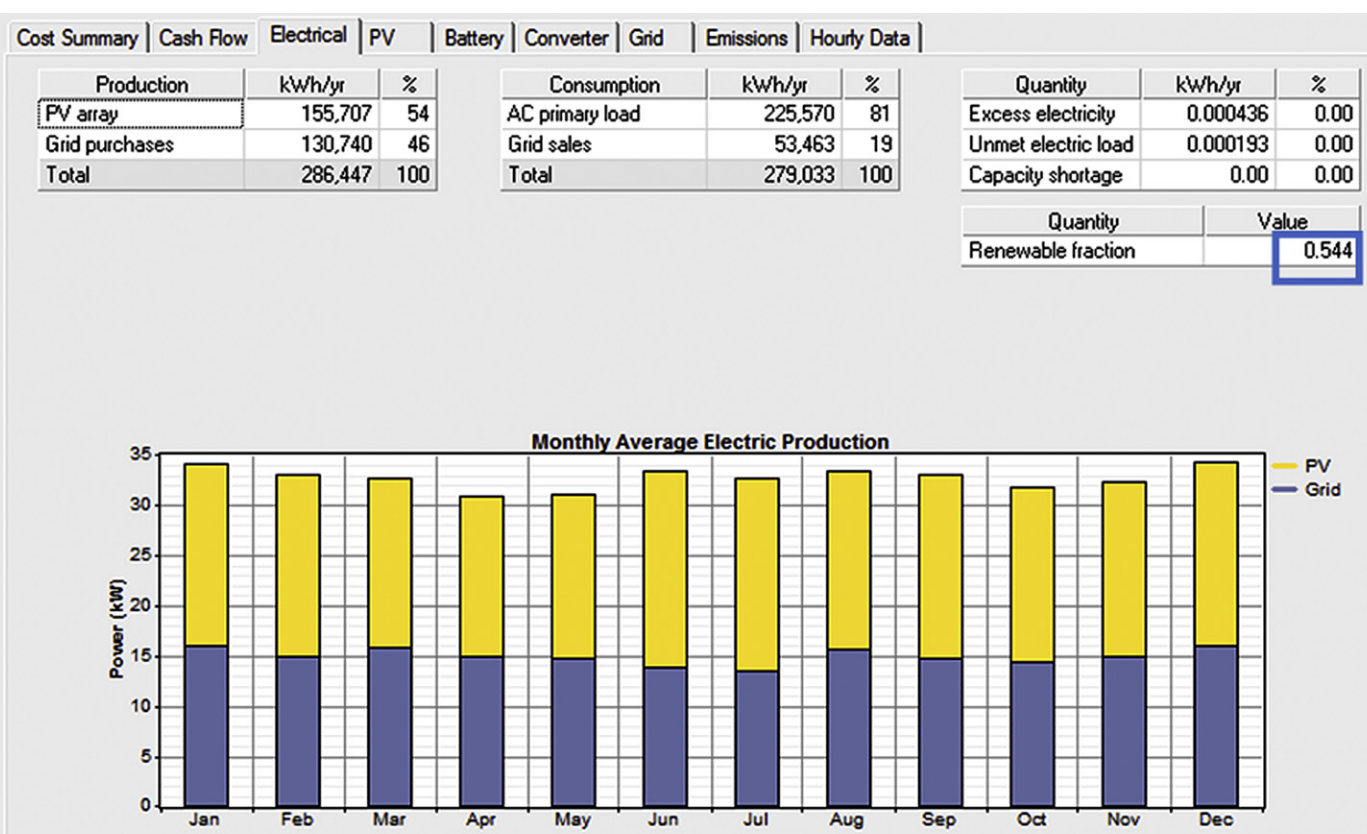


Fig. 14. Monthly average electric production.

From Fig. 14, it can be noticed that the renewable energy fraction has slightly increased to 54.4% compared to only 54% for configuration without energy storage. This is because of a slight reduction in energy purchased from the grid caused by the use of battery system which discharges when PV generator output is low. Therefore this configuration further increases the penetration of renewable energy. To make full use of this system, the use of integrated controller for the battery energy system which has extensive applications in distributed energy systems is recommended. This controller eliminates the need for a separate charging unit for the batteries in the distributed power system network and hence reduces the cost of the energy system [25].

6.5. Emissions

Energy from PV generator is clean because it doesn't use any burning of fuel to extract the energy which would produce produces environmentally and socially dangerous emissions. The energy is extracted directly from sun's radiation. So, there will be no cost subjected to the penalties due to the emission of gases included in annual cost. This means that the application of PV connected systems can reduce the amount of GHG production. For example in Oman, the amount of green house gases reduction due to usage of 5 MW PV system for the 25 locations was presented in [26]. For one site only (Marmul site), a total of 7025 and 5944 tons of GHG could be avoided each year if the 5 MW PV plant is replacing diesel and natural gas based generation, respectively.

7. Conclusion

Uganda's electricity is mainly produced from hydro which is one of the clean energy. Diesel power plants are being used as an alternative to hydro power to reduce the gap between demand and supply of electricity, an exercise which results into some disadvantages. First, the price of fuel is high and therefore the energy produced is also expensive. Secondly, diesel power would not be a better option because of its immediate and long term effect on environment due to carbon emissions and other pollutants that are injected into atmosphere as diesel by-products. In this paper therefore a study has been carried out to explore the possibility of using solar PV systems as alternatives to diesel as a source of electricity in Uganda. It has been established that although the grid only without PV appears to be the cheapest at present, it is not considered as an optimal solution as it does not reduce the dependence on fuel. Grid-connected PV systems without energy storage presents higher NPC, COE but with high level of PV penetration (54%) which guarantees their applicability to reduce on the use of fuel. The grid-connected PV system with energy storage appears to have higher initial capital, operating cost, NPC and COE in the beginning compared with configuration without energy storage but has the highest level of renewable energy penetration (54.4%). The paper has therefore established that PV connected systems can be used as alterative to diesel power and reduce the dependence of non-renewable sources and at the same time reducing the cost of energy in the future.

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