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A design approach of off-grid hybrid electric microgrids in isolated villages: a case study in Uganda

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Abstract

Rural electrification in isolated areas of developing countries can be considered a pivotal factor for economic and social growth, moreover the absence of electricity grid in villages leads to an elevated usage of diesel generators that entails large costs and high CO_2 emissions. This paper presents a design methodology and economical evaluation to implement a hybrid power system composed of a photovoltaic power plant, electrical storage and a backup system of diesel generators in an isolated village in Uganda named Ntoroko. Results show that the usage of battery storage is economically crucial, particularly in areas with a low daily electrical consumption and peak loads increasing in the early morning and late evening when the solar radiation is lower and PV array has a reduced power production. Results disclose that the optimal configuration of the hybrid system (PV-storage-diesel generators), despite its high investment cost, presents an economic benefit of 25.5 and 22.2% compared to the usage of only PV array and diesel generators and only diesel generators and a reduction of fuel consumption equal to 74.7 and 77%, respectively.

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Keywords: Hybrid systems; Solar radiation; Optimization; Off-grid; Electric storage; Photovoltaic systems

Introduction

According to the World Energy Outlook Special Report [1], in Sub-Saharan Africa less than 10% of the rural population has access to electricity and increasing access to modern forms of energy is crucial to unlocking faster economic and social development in this part of the world. The implementation of hybrid systems in isolate and remote rural regions can not only improve the standard of living and the economic growth of the entire region but can also reduce the greenhouse gas emissions, encouraging the environmental respect compared to the diesel generators based energy systems. Some authors [2-4] analysed the implementation of hybrid power systems through the usage of H.O.M.E.R. (Hybrid Optimization Model for Electric Renewable). In 2013 a model was developed to find out the optimal size of grid independent PV-battery-diesel based hybrid energy system in remote villages of Uttar Pradesh in India in order to minimize the Life Cycle Cost and to reduce the CO_2 emissions from the system [5]. In

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2014 a model to generate a comprehensive, cost-optimized electricity plan considering different technology options was implemented and applied to many un-electrified communities in Ghana [6]. The present study uses diesel generators as backup of the hybrid system rather than micro gas turbines [7] to avoid problems related to the high ambient temperature on the electrical efficiency of the latter [8]. Within the current work, the Total Life Cycle Cost (TLCC), discounted throughout 25 years, is evaluated for many different combinations of PV array, electric storage and diesel generators in order to find out the optimal configuration of a hybrid power system. Apart from the economic duty, the optimal configuration is chosen between those that present a percentage of wasted energy minor than 30%. This restriction is due to the fact that the over produced energy in off-grid plants has a high impact of the PV array thermal wear since it cannot be supplied to the grid. The presented work considers a small village in Uganda where there is not an electric grid and currently electricity is supplied by diesel generators. In order to evaluate the supply reliability of a hybrid power system, the electrical load of the entire village and power production of the selected hybrid systems are simulated by running a simulation through an in-house developed MatLab programming code. Compared to the past studies, this work analyses the power system by running a 15 minutes step simulation for one year, in order to evaluate the supply reliability of the system within shorter time step, and therefore to investigate the renewable energy (RE) criticality. Two different configurations are carried out: PV-storage-generators (S1) and PV-generators (S2) and, in order to make a comparison with the current power system of the village, the simulation is implemented also considering only the diesel generators (S3). Sensitivity analysis is eventually carried out to observe how the TLCC of the optimal system configuration varies depending on critical parameters such as diesel cost and interest rate.

Methodology

In order to figure out the optimal hybrid system configuration able to satisfy the required load at the lowest TLCC and with less than 30% of wasted energy, the present study simulates 25 different photovoltaic array sizes, 25 different capacities of battery storage, an inverter and two or more diesel generators. The simulated hybrid system works based on a load-following strategy described below:

- If the solar radiation is adequate, PV power is used to supply directly the load and the possible surplus power is used to re-charge the electric storage until its maximum capacity.
- When PV production is not sufficient, the load is supplied also by the battery storage.
- If the PV power production is not sufficient and the electric storage cannot longer supply the load, the power is fed by the diesel generators.

The simulation is carried out every 15 minutes for 365 days in order to observe in detail how a sudden variation of solar radiation affects the system reliability and, therefore, the potential system configuration. The economic evaluation considers the average year projected along the entire lifetime of the system, taking into account the interest rate to estimate future expenses. Given the electric demand profile, the configuration of the hybrid system is build up through five main steps:

1. Selection of diesel generators combination that satisfy the load in the worse case (no PV production).
2. Evaluation of the available global solar radiation for an entire year and estimation of PV production.
3. Estimation of the range for PV plants size and electric storages capacities.
4. Evaluation of TLCC on each system configuration and identification of those with the lowest values.
5. Identification of the configuration with lowest TLCC and wasted energy less than 30% as the optimal.

2.1 Diesel Generators

The dimensioning process of the diesel generators combination is based on the values of the maximum and minimum peaks electric load and it consists in combinations of different sizes of diesel generators. To ensure a continuous electricity supply service and to reduce the extra power produced by the diesel generators and the fuel consumption each generator can operate at 40%, 60%, 75% or 100% of its rated power and the combinations are sized according to the following restrictions:

1. The sum of the rated powers is equal or grater than the 110% of the maximum peak electrical load demand, the excess power can be used to cover the spinning and/or reserve power as a result of temporary changes in electrical load.
2. The 40% of the rated power of the smallest generator has to be bigger or equal to the baseload, this restriction ensures that the minimum peak load is fed by the lowest consumption condition corresponding at the smallest amount of wasted energy.
3. The rated power of the n^{th} generator has to be bigger or equal to the 40% of the rated power of the $(n+1)^{th}$ generator. This restriction ensures that there is no energy gap between two consecutive sizes of generators, and the demand is still fed by the lowest energy consumption condition.

The simulation optimizes the number of diesel generators: it initially evaluates if at least one or more couples of diesel generators are able to satisfy the above constraints, otherwise it calculates combinations with a generator more until the simulation finds out the combination that minimizes costs.

2.2 Photovoltaic Plant and Electrical Storage

The 25 simulated different sizes of PV array are chosen considering the values between the 10% and the 400% of the maximum electrical peak load, this range is selected following preliminary tests that have been performed in order to find out the more acceptable and reasonable values to simulate the optimal PV system design. The 25 simulated sizes of storage are picked within the range of values between the 10% and the 150% of the mean daily electrical consumption. The battery charging process from PV array begins when the PV production exceeds the electric load demand, Equation (1), and the discharging process starts when the PV array production is no longer able to satisfy the load, Equation (2).

$$S_b(i) = \begin{cases} S_b(i-1) + E_{PV}(i)\eta_c & if\ S_b(i-1) + E_{PV}(i)\eta_c < B \\ B & if\ S_b(i-1) + E_{PV}(i)\eta_c \geq B \end{cases} \tag{1}$$

$$S_b(i) = \begin{cases} S_b(i-1) - \frac{D_i}{\eta_d} & if\ S_b(i-1) - D_i > B(1-DOD) \\ B\ (1-DOD) & if\ S_b(i-1) - D_i \leq B(1-DOD) \end{cases} \tag{2}$$

where, $S_b(i)$ is the storage capacity at time *i* (kWh), E_{PV} is the energy from PV array at time *i* that exceeds the energy load demand (kWh), η_c and η_d are the charging/discharging efficiencies, B is the nominal capacity of the battery (kWh), D(*i*) is the energy requested by the load at time *i*, and *DOD* is the Depth Of Discharge of the storage.

2.3 Economic evaluation

The economic evaluation of the simulated hybrid systems is carried out through the Life Cycle Cost Analysis (LCCA). The LCCA of a system includes the cost of investment of the entire system (initial expenses), the operational and maintenance costs, the repair cost, the replacement cost of the components of system depending on their lifetime, and the residual cost of each component at the end of the lifetime of the system. The present study allocates the investment cost at the year 0 and all the future expenses as a yearly cost depending on the single component from year 1 until the end of the hypothesized system lifetime. Once all pertinent costs have been established and discounted to their present value, they can be summed to generate the Total Life Cycle Cost (TLCC) of the system.

Case Study

The design approach presented in this study aims at figuring out the optimal stand-alone hybrid power system configuration for a village in Uganda named Ntoroko (Latitude 1.05; Longitude 30.53). The village counts about 2’000 habitants and currently is not reached by the national electric grid, therefore the electricity is totally supplied by diesel generators. Load profile data of the considered village are fundamental to evaluate the optimal system configuration. Because of the absence of electric load monitoring systems and of the low level of electricity consumption information, the daily load profile of the village is defined considering the number of electric devices currently used and the living and working activities of the inhabitants. Two load profile trends are considered: the weekday and the weekend load profiles, the last one presenting a lower electricity consumption due to the factories and shops closures during the weekends. The village is located within the equatorial zone where there is little distinction between seasons and solar daily hours are constant during the entire year. The electric load is classified in three different categories which affect the load profile at different times of the day: fridges, lights, and others (TVs, computers, and factories). The mean electrical daily consumption equals to 1680 kWh, the maximum electrical peak load corresponds to 140 kW while the base load is 20 kW. The load profile trend of weekdays can be observed in Figure 1 (blue dashed line) and shows two main peak demand periods occurring in the early morning around 6 AM and in the evening (7-22 PM) mainly due to the increase in usage of lights. The simulation runs with radiation solar data registered every 15 minutes for 365 consecutive days of an entire year (01/01/2005-31/12/2005). The 25 simulated PV array sizes range between 30 kWp and 550 kWp, corresponding at the 10% and the 400 % of the maximum electrical peak load, while the 25 simulated battery capacities vary between 160 kWh and 2500 kWh, that correspond to the 10 % and 150 % of the mean daily electrical consumption. Figure 1 shows the charging and discharging process of six storage capacities for three different simulated PV arrays during an entire day (18th of August 2005). The left y-axis of each sub graph refers to the batteries capacity (kWh), while the right y-axis is expressed in kW and refers to the PV array power and the electrical load profile.

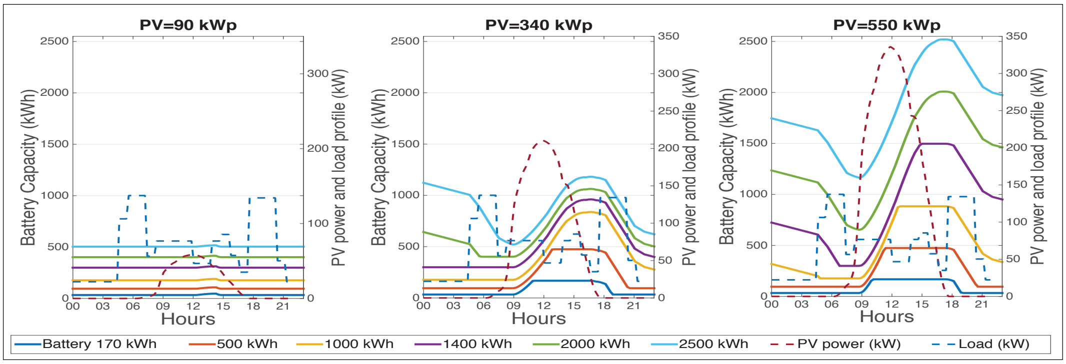

Figure 1: Battery charging and discharging process with two different PV array sizes on the 18th of August 2005.

The charging and discharging process varies significantly with the PV size: when PV size is 90 kWp the battery is slightly charged around 1PM when the load is reduced and the PV power exceeds the electrical load for about 60 minutes. Concerning the PV array size of 340 kWp, the electrical storages of 170 and 500 kWh reach their nominal capacity and are completely discharged until the fixed DOD value during the evening hours, when PV has not power production and the electrical load increases. Eventually, when PV size is 550 kWp, batteries until 1400 kWh (purple lines) are fully charged for at least three hours per day and totally discharge during the evening and night.

Results and Discussion

The design process ends with choosing the system configuration that corresponds at the lowest value of TLCC with percentage of wasted energy lower than 30% for both the systems with storage (S1) and without storage (S2). These results are compared with the TLCC of the current diesel generators based system (S3). Table 1 shows the three optimal configurations S1, S2, S3, their economic evaluation and yearly fuel consumption.

Table 1. Design of the optimal hybrid power system combination with/without storage and only generator system.

Configuration System	Optimal PV array size (*kWp*)	Optimal storage capacity (*kWh*)	Optimal Diesel Gen. (*kW*)	TLCC (*$*) (over 25 years)	Yearly diesel cons. (*L/year*)
S1	340	880	110-50	1’228’800	41’026
S2	160	-	110-50	1’649’600	162’070
S3	-	-	110-50	1’580’100	176’510

These results are carried out considering the diesel cost in Uganda equals to 1.5 $/L (including cost of transport and any other extra costs) and a fixed value of interest rate over the years equal to 11% (current value). Economic data of PV, storage and generators refers to previous studies [3-6]. Table 1 shows that, compared to the current power system S3, the usage of S1 reduces the TLCC over the entire system lifetime of 22.2% and fuel consumption has a reduction of about 77%. On the other hand, the configuration S2, compared to S3, presents a small reduction of fuel consumption (about 8%) and, due to the high investment cost of the PV plant, it does not bring about an economic improvement and the TLCC is 4.4% larger than the one of the S3. In S1 the electric storage has a crucial role for energy saving and cost reduction especially in the presented case study where the peak loads arise in the early morning and late evening when the solar radiation is low and PV array has a reduced power production. In S1 the storage spreads the PV energy in the evening and, for larger capacities, also in the early morning reducing drastically the fuel consumption with a reduction 74.7% of compared to S2 and a resulting reduction of TLCC equal to 25.5%. In order to illustrate the mean monthly energy supplied by PV array and diesel generators in the configuration S1, S2 and S3 during a year, Figure 2 is presented.

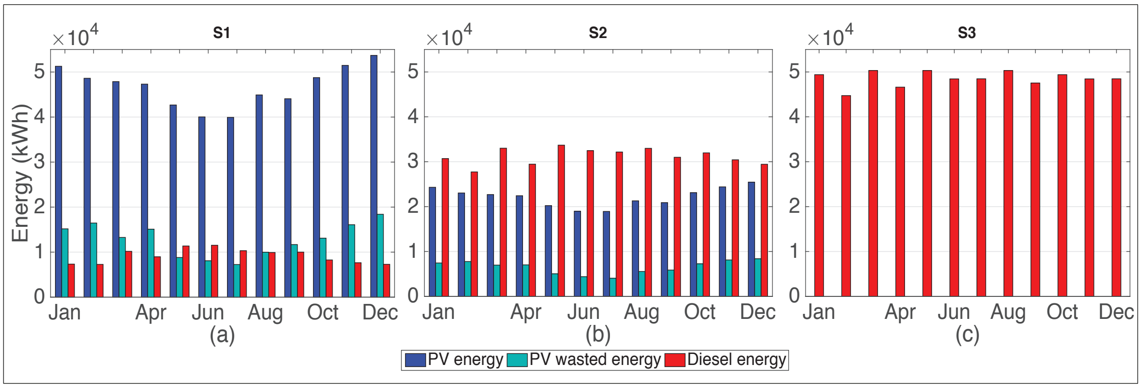

Figure 2: PV array energy, PV wasted energy and diesel generator energy of each month for the hybrid system with electric storage-S1 (a), without electrical storage-S2 (b), and only generator system-S3 (c).

The percentage of wasted energy (light blue bars) is always below 30% of the energy supplied by the PV plant and the mean monthly value of wasted energy corresponds to 27.36% and 29.3% for S1 and S2 respectively. It can be observed that the system S1, besides the low percentage of wasted energy, presents a significant lower values of energy supplied by the diesel generators (red bars) compared to the S2 and S3.

Concerning the configuration S2, it can be observed that each month the energy supplied by diesel generators exceeds the energy supplied by PV, during a year the 67% of energy is supplied by generators and 33% by PV array. Figure 2c shows the monthly energy supplied by S3, where diesel generators are the only power source. The presented results have been evaluated through constant values of parameters that might change during the lifetime of the system, as the fuel cost and the interest rate. In order to observe how these changes might affect the results, sensitivity analysis is eventually carried out. In Table 2 it is illustrated how the TLCC of each optimal system configuration varies considering an increase of fuel cost during the lifetime.

Table 2. Sensitivity Analysis on fuel price increase during the lifetime of the system

Increase of fuel price	50%	80%	100%	150%
TLCC of S1	1'147'800	1'520'400	1'551'100	1'627'800
TLCC of S2	2'616'200	2'808'300	2'929'500	3'232'600
TLCC of S3	2'369'200	2'561'300	2'682'500	2'985'600

Conclusions and future work

The results of the presented study disclose that the optimal combination of PV array, electric storage and back-up system, despite its high investment cost, is the most convenient. The hybrid system presents a reduction in both total costs and fuel consumption compared with the PV-diesel generators and only diesel generators system. This conclusion leads the authors to claim that the electric storage is a fundamental tool to take advantage of renewable and not programmable energy sources, to reduce power production costs (22.2%) and drastically decreasing the fuel consumption (77%), especially in isolated areas where the over-produced power can not be put into the grid and it is wasted. A potential further develop of the presented study is the introduction of micro-wind turbines contribution to the presented hybrid power system with PV, storage and diesel generators and to observe the changes of total cost of the system, fuel consumption and storage effect.

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Biography

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