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Optimal Design of Hybrid Renewable Energy for Tanzania Rural Communities

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Abstract

Rural communities in developing countries lack access to electricity due to high costs of grid extension. This paper proposes a hybrid system of renewable energy (HRES) as solution. The HRES consists of solar, wind, and battery energy storage (BES). The village called Ngw'amkanga in Shinyanga region of Tanzania, East Africa is selected as a case study. An iterative method to determine the size of wind and solar photovoltaic (PV) generation required assuming a project life of 25 years at minimum annualised cost of the system (ACS) is proposed. The project life time is fixed on the life span of the main component, solar PV at 25 years. The iteration is undertaken to meet the energy demand ensuring the BES is charged throughout the year. The required BES has three days of autonomy, and a maximum battery depth of discharge 50%. At minimum ACS, the HRES comprises only solar PV and BES, due to insufficient wind at this site. The levelised cost of energy ($LCOE$) of the HRES is 27.18 p/kWh, paid by the users. This is cheaper than the grid connected small power producers of Tanzania as discussed in the paper.

Keywords: Renewable energy; wind energy generation; solar photovoltaic; annualised cost of the system; levelised cost of energy.

Introduction

Social development and economic growth strongly depend on affordable and reliable electrical energy. Therefore, universal access to electricity is imperative for all nations and the global community at large, especially in the digital age one lives in today. Most of the electrical energy consumed globally is generated from fossil fuels that contribute to greenhouse gases (GHGs) emissions to the atmosphere (Akodere et al. 2010). The International Energy Agency (IEA) report showed that 60% of electricity supply worldwide is from coal and gas (International Energy Agency 2020). In order to minimize energy-related GHGs emissions, the world has started utilizing renewable energy resources (RERs) such as solar, wind and biomass energy resources for electrical energy generation. This is the basis for initiatives such as SE4ALL (Sustainable Energy for All 2019). Referring to IEA report, RERs contribute about 30% of global electricity supply (International Energy Agency 2020). The downward trend in costs of renewable energy technologies such as the decrease of unit cost of solar photovoltaic (PV) modules has also accelerated the increase in installed renewable energy generation capacity (Diwania et al. 2019).

Renewable energy resources are environmentally friendly because they produce clean and sustainable energy. Among the different types of RERs, solar and wind energy resources are freely available and are replenished naturally compared with fossil fuels which cannot be replenished. It is claimed that the sunlight striking the earth in one hour produces more energy than the world's annual energy consumption (Zhang et al. 2013). Renewable energy (RE) generation can be either integrated to the grid or deployed in small independent electricity networks known as microgrids. Renewable energy generation and indeed any other type of generation connected to the grid distribution networks are referred to as Distributed Generation (DG). With renewable DG, the energy generated by fossil fuels is reduced leading directly to reduced GHGs emissions.

In an off-grid microgrid, RE generation provides cheap energy to people without access to the electrical grid and provides notable money and pollution savings (Bianchini et al. 2015). This is because the RE system does not need costly long transmission network and associated losses. Depending on the availability of RERs at a location, only one energy resource or a combination of different energy resources can be employed in an off-grid microgrid. For example, a microgrid can consist of solar photovoltaics (PV) or wind turbines or both. A system that comprises more than one renewable energy resource is referred to as hybrid renewable energy system, in short HRES (Srivastava and Banerjee 2015).

The power output from RERs such as solar and wind energy normally fluctuates owing to variable nature of these resources. These power output fluctuations can be short-term or long-term (Passey et al. 2011). For example, solar energy short-term fluctuations occur during daytime when solar irradiation keeps changing, and long-term fluctuations occur during night hours when solar insolation is zero. Therefore, off-grid microgrids must have energy storage system (ESS) to store excess energy and provide the stored energy back to the system when needed. An energy storage system is not essential in grid-connected RE system because when power fluctuates, power can be fed to the grid or drawn from the grid. There are various types of ESS such as hydrogen, compressed air, pumped hydro, and batteries (Passey et al. 2011). Moreover, RE generations need a power electronic converter interface to connect to the grid (grid-connected system), or to the end users that is, off-grid microgrid systems (Blaabjerg et al. 2006). For example, solar PV generates direct current (DC) electricity, but end users consume alternating current (AC) electricity, therefore a power electronic inverter should be incorporated to the system to convert electricity from DC to AC.

The World Energy Outlook 2019 estimated that about 850 million people around the world (11% of the world's population) have no access to electricity (International Energy Agency 2019). Out of the 850 million people, 600 million are in Africa. In Tanzania Mainland, there is 78.4% access to electricity by the year 2019-2020 (URT 2020). Lack of electricity to these people is mainly caused by lack of financial capacity to meet the costs of electricity supplied by the grid, that is the tariff. For example, in Tanzania, the current tariff of small power producers (SPPs) selling to the grid is 7.67 p/kWh for solar PV, and 7.88 p/kWh for wind (The Electricity Order 2019). This tariff is what the grid pays to the SPPs. The grid will have to charge the customers additional costs to cover for other operational, maintenance, and loss costs, thus making the customer tariff higher and not affordable to many. Loss costs account for the transmission electrical power losses. `

According to the findings of Energy Access and Use Situation Survey II in Tanzania Mainland conducted in 2019/2020, only 61.7% of the total population in Shinyanga region has access to electricity (URT 2020). However, the percentage of rural households that have electricity connection in Shinyanga region is only 16.2% by 2019/2020. Ngw'amkanga village is among the villages in Shinyanga region with no electricity from the main grid, which is located about 20 km away. The total number of households in Ngw'amkanga village is 531, with a total population of 3,068. Living without electricity forces these people to stay in poverty. Therefore, in this paper, an affordable microgrid HRES is designed for the Ngw'amkanga village rural community with the aim of improving the social and economic status of the community thereby reducing poverty.

Materials and Methods

Case study description

The selected rural community for this project is the village called Ngw'amkanga found in Shinyanga region of Tanzania in Africa. The village is located at 3.6143 °S latitude, 33.1689 °E longitude, and 1,132 m above sea level. According to the findings of Energy Access and Use Situation Survey II in Tanzania Mainland conducted in 2019/2020, only 61.7% of the total population in Shinyanga region have access to electricity. However, the percentage of households that have electricity connection in Shinyanga region is only 16.2%. Ngw'amkanga village is specifically chosen because it has solar and wind energy resources, and does not have access to electric energy from the main grid. Most families in Ngw'amkanga village spend the morning time doing farm works, and after lunch engage in other activities such as baskets and mats weaving at their premises.

Load modelling

Load modelling for the selected rural community is the initial step in the design of the HRES. Firstly, the information about the total number of people and families of the selected community was obtained from the village chairperson. Secondly, a questionnaire survey method was developed to collect data about electrical appliances the villagers expect to have if they have access to electricity. The survey was conducted to a sample of ten households that are chosen by looking at different sizes of families, and their economic status. Other information about the used electrical machines such as water pumps, cereal peeling and milling machines needed by the community was obtained from the village chairperson. Thirdly, the power ratings of the appliances and electrical machines were determined along with their daily usage. The power ratings of the appliances were obtained from Daft Logic (2020). Fourthly, the diversity factors were used to obtain the total power demands of the whole community in every hour because not all families' appliances will be switched on at exactly the same time. The diversity factors used are from Schneider Electric (2016, pp. A19–A21). In Tanzania, solar PV power projects use similar diversity factors for the existing projects. Finally, daily load curve is developed by plotting hourly power demands in kilowatt (kW) against time in hours.

Solar PV module modelling

Microsoft Excel was used to model the solar PV module and to calculate annual hourly power output of the solar PV module. The output power of the solar PV module at time t ($P_{PV}(t)$) was determined by the following parameters: solar PV module efficiency (η_{PV}), solar PV module area (A_{PV}) in m^2, site solar irradiation at time t ($G(t)$) in kWm^{-2}, temperature coefficient of the solar PV module at maximum power (β), cell temperature (T_c) in °C, and reference temperature (T_{ref}) in °C. The output power of the solar PV module was calculated by the following Equations (Kaabeche et al. 2011):

$$P_{PV}(t) = \eta_{PV} \times [1 - \beta \times (T_c - T_{ref})] \times A_{PV} \times G(t), \quad (1)$$

$$T_c = T_{air} + \frac{G(t) \times (NOCT - 20^0 C)}{800}. \quad (2)$$

Where T_{air} is the ambient air temperature in °C and $NOCT$ is the nominal operating cell temperature in °C.

Wind turbine modelling

Microsoft Excel was used to model wind turbine generator and to calculate its annual hourly power output. The wind turbine generator power output at any time t ($P_w(t)$)

depends on the wind speed at time t ($V_w(t)$) in ms^{-1}, wind turbine power coefficient (C_p), air density (ρ) equal to 1.22 kgm^{-3}, wind turbine efficiency (η_w), and the area swept by the wind turbine blades (A_w) in m^2. Power output of the wind turbine was calculated by the following Equation (Addo et al. 2014):

$$P_w(t)=\begin{cases}0.5\times C_p\times\rho\times\eta_w\times A_w\times(V_w(t))^3 & \text{if } V_{ci}\le V_w(t)<V_r,\\ P_{r,w} & \text{if } V_r\le V_w(t)<V_{co},\\ 0 & \text{if } V_{ci}>V_w(t)\ge V_{co},\end{cases} \quad (3)$$

Where $P_{r,w}$ is the rated power of the wind turbine generator, V_{ci} is cut-in wind speed, V_r is rated wind speed, and V_{co} is cut-off wind speed.

Battery storage modelling

Battery energy storage (BES) is used to store excess energy when the energy generated is greater than the energy demand, or supply the load when the energy generated is less than the energy demand. Excess energy is dumped when the batteries are fully charged to avoid overcharging, and the load is disconnected when the batteries are discharged up to their minimum state of charge ($SoC_{\min}$) to avoid damaging the batteries. When the energy generated is equal to the load demand the state of charge (SoC) of batteries remains constant. The state of charge of the battery bank at any time t ($SoC(t)$) in per unit depends on the previous state of charge ($SoC(t-1)$) in per unit, battery bank voltage (V_{bb}) in volts, and battery bank capacity in ampere-hour ($C_{bb,Ah}$). The $SoC(t)$ is given by the following equation (Li et al. 2012):

$$SoC(t)=SoC(t-1)+\frac{(N_w\times P_w(t))+(N_{PV}\times P_{PV}(t))-P_L(t)}{V_{bb}\times C_{bb,Ah}}, \quad (4)$$

Where $P_L(t)$ is the power demand at time t, N_w is the number of wind turbines, and N_{PV} is the number of solar PV modules. Battery self-discharge rate, charging efficiency, and discharge efficiency are considered negligible and therefore neglected. The maximum state of charge ($SoC_{\max}$) of the battery bank is one unit when the battery bank is fully charged. The $SoC_{\min}$ of the battery bank depends on the battery bank maximum depth of discharge ($DoD_{\max}$), hence $SoC_{\min}=1-DoD_{\max}$. Therefore, $SoC(t)$ of the battery bank is kept within this range: $SoC_{\min}\le SoC(t)\le 1$.

Battery sizing

Battery bank capacity is calculated taking into account the $DoD_{\max}$ of the battery bank, daily energy demand (E_D) of the selected community, and days of autonomy (DA) when only the battery storage will supply the entire load demand without being charged by any power source. The required $C_{bb,Ah}$ is calculated using the following Equation (Kaabeche et al. 2011):

$$C_{bb,Ah}=\frac{E_D\times DA}{V_{bb}\times DoD_{\max}} \quad (5)$$

The selected battery rated capacity in ampere-hour ($C_{b,Ah}$) and rated voltage (V_b), respectively were applied in determining the number of batteries required in the system. The number of batteries in parallel ($N_{b,parallel}$), the number of batteries in series ($N_{b,series}$), and the total number of batteries (N_b) were calculated using Equations (6) to (8) (Yazdanpanah 2014).

$$N_{b,parallel}=C_{bb,Ah}/C_{b,Ah} \quad (6)$$

$$N_{b,series}=V_{bb}/V_b \quad (7)$$

$$N_b=N_{b,parallel}\times N_{b,series} \quad (8)$$

The total number of batteries was obtained using Equation (8) because $N_{b,parallel}$ signifies the number of parallel paths or branches, and $N_{b,series}$ signifies the number of batteries connected in series in each parallel branch.

Wind generation and solar PV generation sizing

An iterative method proposed by Geleta and Manshahia (2018) is used to determine the number of wind turbines (N_w) and number of solar PV modules (N_{PV}) required to charge the battery bank, and to ensure the energy demand of the selected community is met throughout the year. Given the following parameters: $P_w(t)$, $P_{PV}(t)$, $P_L(t)$, $SoC(t)$, $C_{bb,Ah}$, and V_{bb} over the time period [t_1, t_{8760}]; N_w and N_{PV} are determined by undertaking the following optimisation process.

$$(N_w \times P_w(t)) + (N_{PV} \times P_{PV}(t)) + \left(\frac{SoC(t) \times C_{bb,Ah} \times V_{bb}}{\Delta t} \right) \geq P_L(t) \quad (9)$$

$$N_w \geq 0 \quad (10)$$

$$N_{PV} \geq 0 \quad (11)$$

$$SoC_{\min} \leq SoC(t) \leq 1 \quad (12)$$

Figure 1 is the flowchart that shows the procedures to obtain the different combinations of N_w and N_{PV} that satisfy the inequalities (9)–(12). The combinations obtained are later examined to select the optimal combination of solar PV modules and wind turbines. The optimal system design is the one with minimum annualised cost of the system (ACS).

Hybrid renewable energy system optimisation

The HRES of solar PV, wind turbines, and BES is optimised to minimise the total lifetime costs of the system. Therefore, different combinations of units of wind turbines and solar PV modules obtained using inequalities (9)–(12) are evaluated by the objective function defined by Equation (13) to determine the combination with minimum ACS (the minimum ACS here is denoted as C_a). This objective function has been used in (Chauhan and Saini 2014).

$$\text{Minimise } : C_a = \sum_N \left(C_{a,cap} + C_{a,rep} + C_{a,O\&M} \right), \quad (13)$$

where $C_{a,cap}$, $C_{a,rep}$, and $C_{a,O\&M}$ are the annualised: capital costs; replacement costs; and operation and maintenance costs of the system components, respectively.

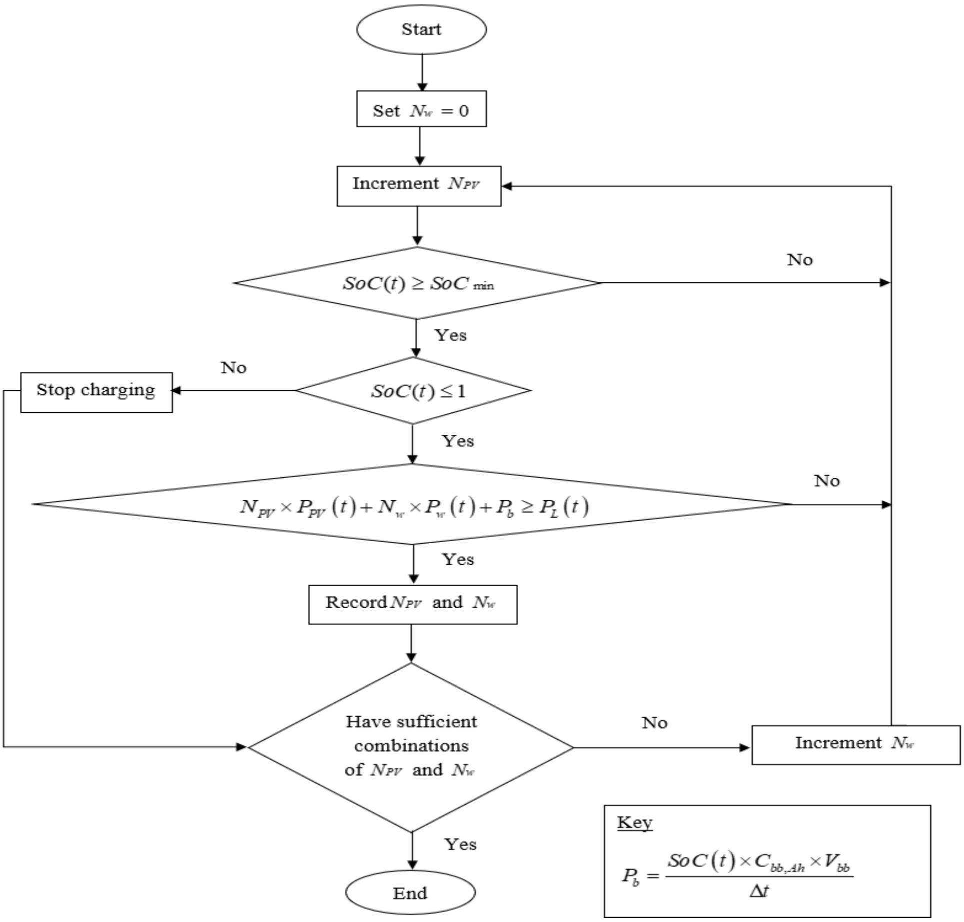

Figure 1: Wind and solar PV generations sizing flowchart.

Economic evaluation

The net present cost (NPC) and levelised cost of energy ($LCOE$) of the optimal energy system design are evaluated. Equation (14) shows the calculation of the total NPC using the total ACS of the optimal solution obtained in Equation (13) and capital recovery factor $CRF(i, R_{proj})$. Project lifetime in years is denoted by R_{proj}, and i is the annual actual interest rate (Chauhan and Saini 2014).

$$NPC = \frac{ACS}{CRF(i, R_{proj})} \qquad (14)$$

The $LCOE$ in pence per kilowatt-hour (p/kWh) is calculated by taking the ratio of the total ACS to the total annual energy generated (E_{annual}) as shown by (Chauhan and Saini 2014) in Equation (15). Since the annual energy output of the solar PV module declines over time, E_{annual} is calculated by an average of all the total annual energy generated over the project lifetime.

$$LCOE = \frac{ACS}{E_{\text{annual}}} \qquad (15)$$

Results

Solar resource assessment

Figure 2 shows annual hourly solar irradiation at Ngw'amkanga village. Further shown in Figure 3, the annual average solar insolation is 6.5 kWhm^{-2}/day, while the average monthly minimum and maximum solar insolation are 5.8 kWhm^{-2}/day in January and 7.2 kWhm^{-2}/day in September, respectively. The solar irradiation and solar insolation data were obtained from Weather Spark website (Weather Spark 2020).

Wind resource assessment

Figure 4 shows annual hourly wind speed at Ngw'amkanga village at 30 m hub height. Further shown in Figure 5, the annual average wind speed is 4.4 ms^{-1}, while the average monthly minimum and maximum wind speed are 2.5 ms^{-1} in January and 6.1 ms^{-1} in August, respectively. The wind speed data were obtained from Weather Spark website (Weather Spark 2020).

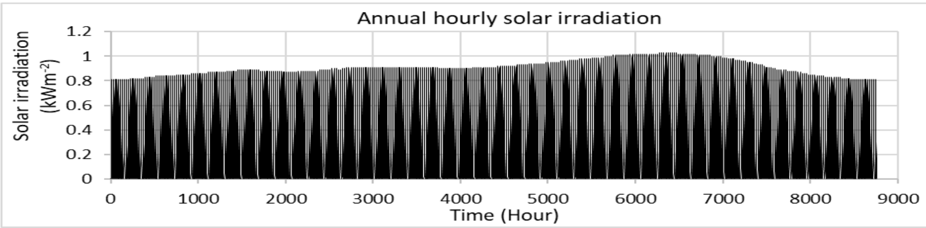

Figure 2: Annual hourly solar irradiation at Ngw'amkanga village.

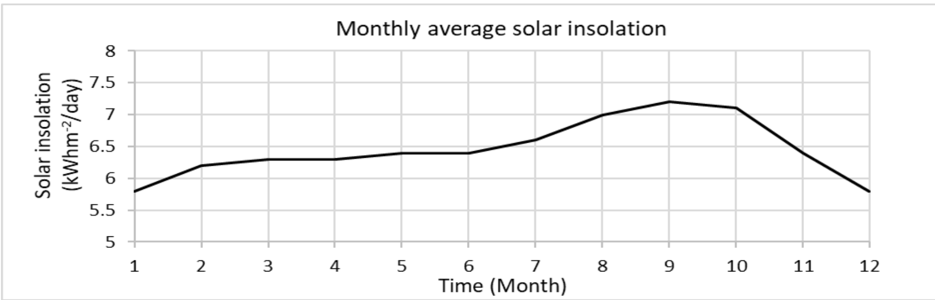

Figure 3: Monthly average solar insolation at Ngw'amkanga village.

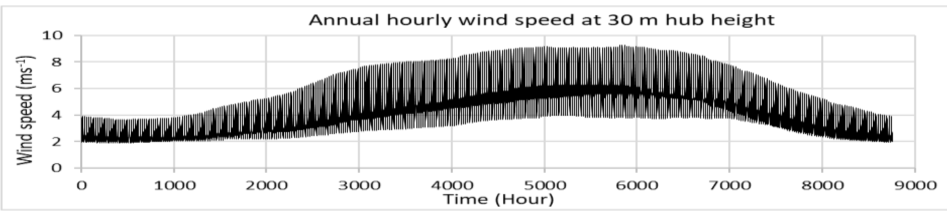

Figure 4: Annual hourly wind speed at 30 m hub height at Ngw'amkanga village.

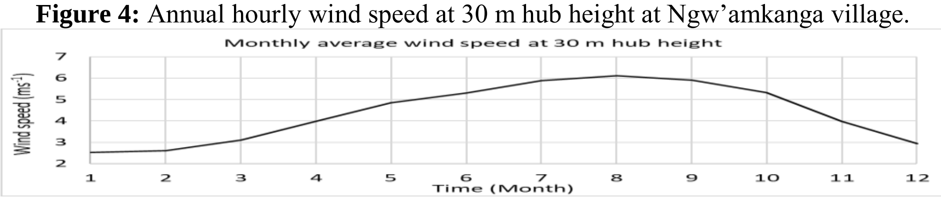

Figure 5: Monthly average wind speed at 30 m hub height at Ngw'amkanga village.

Load modelling

Load modelling was conducted employing the procedures described previously. The total number of households in Ngw'amkanga village is 531, and the total number of people is 3,068. According to the information from the village chairperson, the total number of people over the past ten years has seemed to remain constant. A sample size of 10 households is selected since the families exhibit heterogeneous characteristics: the economic status and size of the family (number of people per family) slightly vary from one household to another.

The results of the questionnaire survey conducted to a sample of ten families showed that all families expected to have the following appliances: light bulbs, radios, television sets, electric kettles, iron, ceiling fans and phone chargers. Out of ten families, five mentioned the need of food blenders, and two mentioned the need of electric cookers and refrigerators. Also, the village chairperson mentioned the need of ten electric water pumping machines and five cereal milling machines. Currently, the village has six manual water pumps and three cereal milling machines powered by diesel generators. The appliances' power ratings from Daft Logic (2020), and the diversity factors from Schneider Electric (2016, pp. A19-A21) were used to estimate the daily load profile of Ngw'amkanga village shown in Figure 6. The peak demand is 188.931 kW at 19:00 and 20:00 hours and daily average load is 97.423 kW. The total daily energy consumption is 2.342 MWh and is assumed to remain constant during this project lifetime. This assumption depends on the fact that the population of Ngw'amkanga village does not seem to change.

Solar PV module modelling

Microsoft Excel was used to model the solar PV module and the power output results are shown in Figure 7. Equations (1) and (2) were used to calculate hourly power output of the solar PV module. The total calculated annual energy output of a solar PV module (HiDM CS1H-335MS) proposed to be installed in Ngw'amkanga village was found to be equal to 788.346 kWh.

Wind turbine modelling

Similar to the solar PV, Microsoft Excel was used to model the wind turbine generator and the power output results are shown in Figure 8. Equation (3) was used to calculate hourly power output of the wind turbine generator. The total calculated annual energy output of the selected wind turbine (Aeolos–H 50 kW) proposed to be installed in Ngw'amkanga village was found to be equal to 50,664 kWh.

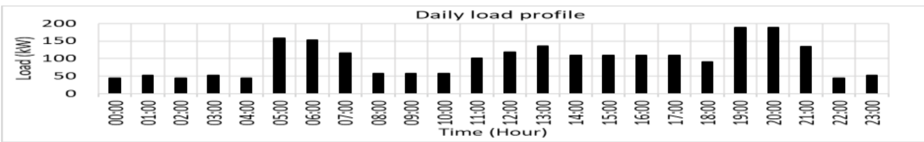

Figure 6: Daily load profile of Ngw'amkanga village.

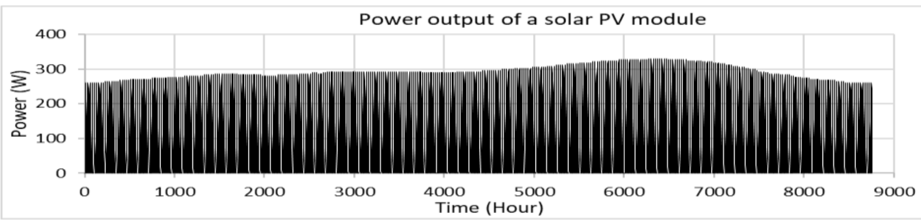

Figure 7: Annual hourly power output of solar PV module.

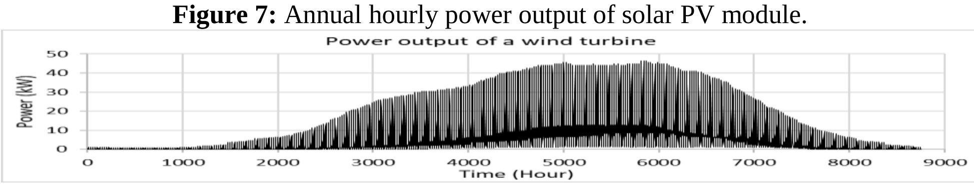

Figure 8: Annual hourly power output of wind turbine.

Battery sizing

The battery sizing method described previously was used to determine the $C_{bb,Ah}$. In this paper, $DA = 3$ and $DoD_{max} = 50\%$ were used to determine the $C_{bb,Ah}$. Using Equation (5), $C_{bb,Ah}$ was found to be equal to 292.5 kAh. Using Equations (6) and (7), the $N_{parallel}$ and N_{series} were 315 units and 6 units, respectively. Therefore, N_b was calculated and found to be equal to 1,890 units.

Wind generation and solar PV generation sizing

The iterative method was employed to determine the size of wind energy generation and size of the solar PV generation. Table 1 shows the results of wind energy generation and solar PV generation sizing. Each combination of units of wind turbines and solar PV modules ensured that the $P_L(t)$ was met and the battery SoC_{min} was maintained.

Hybrid renewable energy system optimization

Different combinations of units of wind turbines and solar PV modules (N_w and N_{PV}) were evaluated by the objective function stated by Equation (13) to determine the optimal HRES. The actual annual interest rate was calculated by Marcel (2020) and found to be equal to 6%. Figure 9 shows the different values of of ACS for different combinations of N_w and N_{PV} units. The $N_b = 1{,}890$ was kept constant for all combinations. The results show that the optimal energy system design for Ngw'amkanga village comprises $N_b = 1{,}890$ units, $N_{PV} = 1{,}903$ units, and $N_w = 0$ unit. The ACS of optimal system was found to be equal to £ 350,765.08.

Table 1: Wind generation and solar PV generation sizing results

Components sizing	Number of feasible solutions					
	1st	2nd	3rd	4th	5th	6th
Solar PV module (N_{PV} units)	1,903	1,902	1,901	1,900	1,899	1,898
Wind turbine (N_w units)	0	1	2	3	4	5

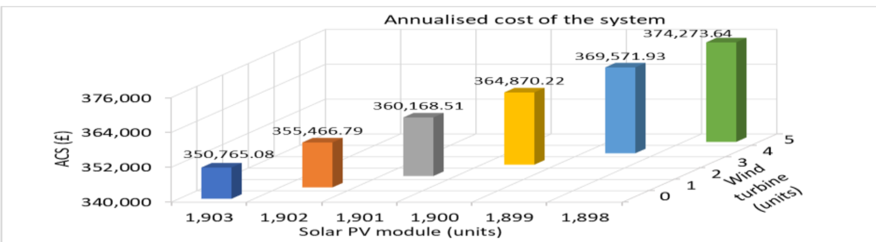

Figure 9: Annualised costs of the system.

Economic evaluation

Net present cost

The NPC of the optimal energy system design was calculated by using Equation (14). Table 2 shows the calculated NPC of individual system components and total NPC of the whole system. The NPC of the whole system was found to be equal to £ 4,706,878.48. The details of obtaining solar inverter units' size and ratings, land size, and their respective costs are covered by Marcel (2020).

Table 2: Net present cost results

Components	NPC (£)
Solar PV ($N_{PV} = 1{,}903$ units)	610,190.04
Batteries ($N_b = 1{,}890$ units)	3,873,764.91
Solar inverters (96 units)	209,056.65
Land (5380 m^2)	13,866.88
Whole system	**4,706,878.48**

Levelised costs of energy

Table 3 shows the levelised costs of energy **(**LCOE) results of the optimal energy system design obtained using Equation (15). This LCOE can be contrasted to the grid connected SPPs tariff for solar and wind of 7.67 p/kWh, and 7.88 p/kWh, respectively (The Electricity Order 2019). This tariff is before the grid accounts for operational, maintenance, losses, and other costs related to power transmission and distribution. It may be argued here that the LCOE computed in Table 3 will be cheaper than the power from the grid connected SPPs.

In performance warranty of the solar PV module (HiDM CS1H-335MS), it is explained that during the first year the energy output of the module is not less than 97.5% of the rated output, and decrease by no more than 0.6% annually from year 2 to year 25. Figure 10 shows the annual energy output of a solar PV module proposed to be installed in Ngw'amkanga village over the project lifetime.

Discussion

Renewable energy resources have the potential to provide clean and affordable electrical energy to communities with no access to electrical energy. This paper has employed an iterative method to design an optimal HRES with BES for Ngw'amkanga village. Both wind energy and solar PV generations were evaluated in this paper. The results show the optimal HRES design consists of solar PV generation and BES without wind energy generation. The village has few windy months (June, July, August, and September) in which the wind turbine power outputs were found at least half of the rated turbine power. December to March were the calm months with four months average wind speed below the wind turbine cut-in speed of 3 ms^{-1}; therefore, in most hours the wind turbine power output was equal to zero.

Table 3: Levelised costs of energy results

Scenario	LCOE (p/kWh)
System with solar PV modules and batteries only	25.89
System with solar PV modules, batteries, and inverters	27.10
System with solar PV modules, batteries, inverters, and land included	27.18

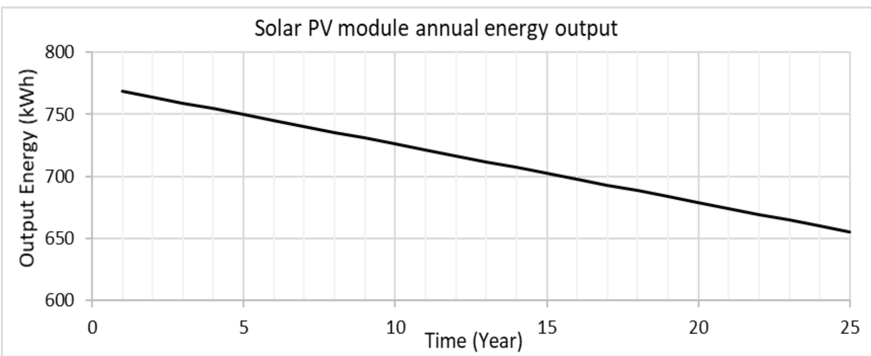

Figure 10: Annual total energy output of solar PV module.

On the other hand, the solar irradiation at Ngw'amkanga exhibit only slight variations throughout the year compared with wind speed, and it is sufficient for solar energy generation. Thus, wind speed and solar irradiation characteristics prove that the energy system strongly depends on the solar PV generation to meet the annual energy demand. Increasing the number of wind turbines only increases the system cost and power to be dumped during few windy months.

The results show that BES NPC is about 83% of total NPC of the optimal HRES. This is due to the high costs of batteries, and high number of batteries included in the system owing to the chosen DA. Storage batteries are also the ones that contributed to high $LCOE$. The NPC and LCOE could be lowered by reducing the N_b in the system, and probably introduce back-up diesel generators in the system to supply the load in some of the days of DA (Gan et al. 2015).

Conclusion

This paper has proposed an optimal HRES of solar PV, wind energy, and BES design for Ngw'amkanga village. The size of the solar PV generation, wind energy generation, and BES of the system installation were calculated. The iterative method used showed that optimal HRES for the village consists of 1,903 solar PV modules, 1,890 battery units, and zero wind turbines. The economic analysis showed that 83% of the total NPC is taken by BES and the same applied to the LCOE. In this paper, the daily load profile was assumed constant throughout the project lifetime. However, in reality there is a high possibility of demand increase because electricity availability will attract different development projects such as establishment of small industries. Furthermore, solar clearance index was not included in the solar PV generation modelling owing to the lack of clearance index data for Ngw'amkanga village. Therefore, the actual energy generated by the solar PV module may be different from the one calculated in this paper because the sky is not always clear from clouds. These two cases will constitute future studies.

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