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Application of renewable energy resources in a microgrid power system

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Abstract: In order to meet the power prerequisites of their citizens, many countries are heavily dependent on the utilization of fossil fuels for power generation. This has reduced the natural reserve of fossil fuels and caused a large percentage of greenhouse gas emissions (GHGs). It is imperative to harness energy from renewable energy resources (RERs) as a measure to supplement the authors' daily energy needs from the conventional units. The proposed microgrid system deals with the incorporation of the wind turbine generator (WTG), diesel generator, hydro turbine, photovoltaic and battery storage system for optimisation of net present cost (NPC), annualised cost of the system (ACS), GHG, fuel cost, operating costs and cost of energy (COE) by using hybrid optimisation model for electric renewables using HOMER software. The system is designed with the energy demand of 618 kWh/day at a peak load of 72.5 kW. The values of NPC, COE, ACS and fuel consumption obtained in the optimised configuration are \$942,654/yr, \$ 127,415, \$0.327/kWh and 51,236 L/yr. The simulation results obtained from the optimised scenario reveal that the utilisation of RERs has been found to be a cost effective means to supply remote areas.

1 Introduction

The rapid rise in population and demand for a continuous power supply has prompted the utilisation of fossil fuels in many countries. Owing to this, the growth in the global economy requires more power demand and the failure of the utilities to meet the power consumption of various consumers has a negative impact on the gross domestic product (GDP). This shows that the world economy depends mainly on the availability of power supply. Presently, 75.5% of global electricity is sourced from fossil fuels while 24.5% comes from renewable energy resources (RERs) [1]. This record indicates over-dependence of the global population on non-replenishable sources of power generation. Moreover, conventional power generation is expensive to run due to extremely high operating and maintenance (O&M) costs and serious health complications that are associated with its operation. The key approach to meet the universal energy sustainability is to encourage the usage of RERs. This objective can be achieved if the stakeholders in the power sector can utilise the available RERs as a prerequisite to meet consumers' power demand [2].

About 17% of the world population is currently living without a power supply due to one reason or another [3]. The 22% of this set of people are living in rural communities of the undeveloped nations where connection to transmission and distribution (T&D) lines are very problematic owing to economic and technical reasons. The remoteness of some rural areas from T&D lines is another cogent factor that hinders them from being connected to the grid [3]. Having considered the economies of scale and financial benefits of using distributed generation to power remote areas, it is prudent to use distributed generation technologies to meet the power requirements of remote areas than to spend a lot of money for extension of the T&D lines to such places [3]. As a result of this, most of the rural communities are powered with the application of diesel generators (DGs) that emit greenhouse gas emissions (GHG) pollutants due to non-accessibility of the rural dwellers to the grid. Moreover, the cost of fuels delivery at the remote areas coupled with the fluctuating prices of fossil fuels makes the cost of energy (COE) from the DGs to become unbearable.

The potential alternative to meet the energy requirements of rural inhabitants without any environmental and economic issues is to incorporate RERs into their power systems [4, 5]. It has been reported by many literatures that RERs are promising solutions to the world energy crisis because they are environmentally friendly and do not cause to global warming when compared with conventional units. Numerous technical, economic and environmental benefits can be derived by the utilities for utilising the accessible solar, water and wind resources for power generation. The installed capacities of hydro power, wind, photovoltaic (PV), geothermal and biomass energy at end 2016 are estimated to be 1096, 487, 303, 13.5 and 112 GW, respectively [1]. Moreover, ∼35% of the global energy supply has been projected to come from RERs by 2030 [6].

Several research works have been carried out on the techno-economic analysis of RERs in a power system. However, there are few studies that show the combination of hydro turbine (HT) with other RERs. Ayodele [7] studies the effects of wind/diesel/battery on a hybrid system in a rural area in Nigeria. Meanwhile, Olatomiwa *et al.* [8] carried out a feasibility study of a PV–wind–diesel hybrid system for rural electrification in Nigeria and Adefarati and Bansal [3] investigated the impacts of PV–wind turbine generator (WTG)–battery storage system (BSS)–DG on the economic and environmental feasibility of power supply in the remote area. In this study, a techno-economic assessment of a microgrid (MG) system that comprises of PV, WTG, BSS, DG and HT is carried out with the application of hybrid optimisation model for electric renewables (HOMER) software based on NASA data. The tool is used to model and optimise the sizes and operation of an MG system by considering the economic and environmental benefits. The results obtained from this research work demonstrate the suitability of an MG system as an alternative to meet the power requirements of remote areas.

2 MG power system

An MG is a small-scale power system that consists of distributed generation and loads. It is designed to operate independently or in parallel with the grid. It is effectively used as a measure to guarantee a reliable and affordable energy for rural dwellers. The models of the components that constitute the MG system are discussed in this section.

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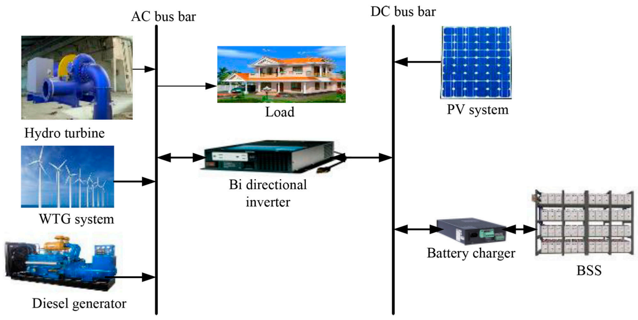

Fig. 1 *PV/BSS/WTG/HT/DG MG system*

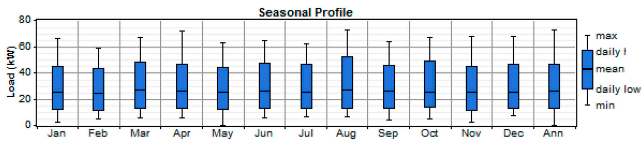

Fig. 2 *Seasonal profile of the considered load*

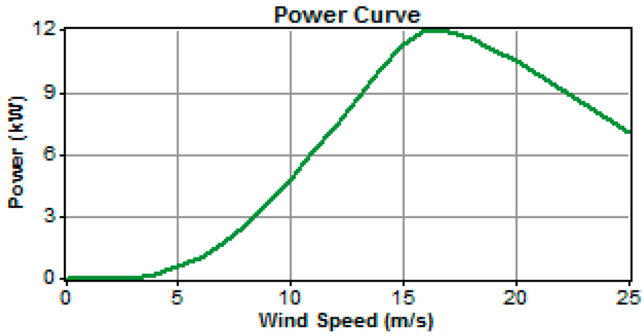

Fig. 3 *Wind turbine power curve*

2.1 Power balance of an MG system

The power balance of the MG system as presented in Fig. 1 can be expressed as follows:

$$P_{\mathrm{D}} = P_{\mathrm{HT}} + P_{\mathrm{WTG}} + P_{\mathrm{PV}} + P_{\mathrm{DG}} \pm P_{\mathrm{BSS}}, \ \mathrm{kW} \quad (1)$$

where P_{D} is the load demand, P_{BSS} is the BSS charge and discharge power and P_{DG}, P_{PV}, P_{WTG} and P_{HT} are the power generated from DG, PV, WTG and HT, respectively. The seasonal load profile that is used in this study is presented in Fig. 2. The load selected for this work is located in the remote area in Free State province of South Africa.

2.2 Wind turbine system

The modelling of wind turbines for power generation application is based on the tower height, velocity speed exponent, wind shear and turbine wind characteristic [9, 10]. The power output of the WTG can be estimated by using the expression presented in (2) as [11]

$$P_{\mathrm{WTG}} = \frac{1}{2}\rho A v^3 C_{\mathrm{p}} \eta_{\mathrm{g}} \eta_{\mathrm{b}} \quad (2)$$

where v is the wind speed (m/s), η_{g} is the generator efficiency, η_{b} is the gear/bearing efficiency is the air density (kg/m^3), A is the turbine rotor swept area (m^2) and C_{p} is the coefficient performance. The power curve for the WTG unit and the average wind velocity of a site that is located at Free State province of South Africa are presented in Figs. 3 and 4.

The Weibull probability density function (PDF) is utilised in this study to illustrate the rule of wind speed variation. The function is expressed in (3) as [12]

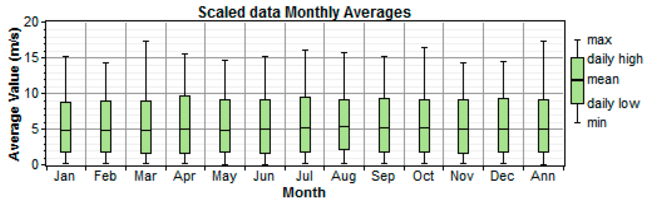

Fig. 4 *Monthly average wind speed*

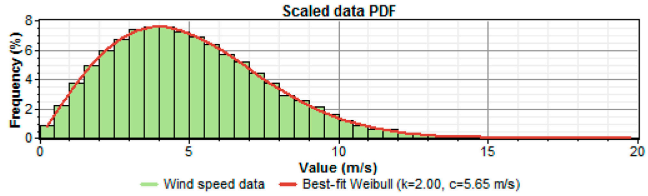

Fig. 5 *PDF*

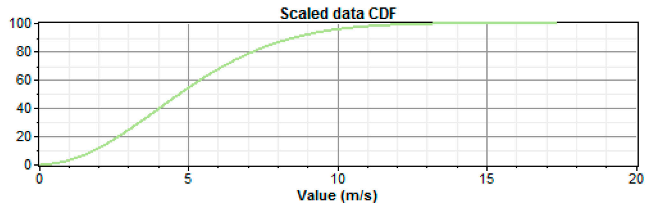

Fig. 6 *CDF*

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp^{\left[-(V/c)^k\right]} \quad (3)$$

where k is the shape factor, v is the wind speed (m/s) and c is the scale factor. The cumulative distribution function (CDF) is represented in (4) as [12]

$$F(v) = \left(1 - \exp^{-(v/c)^k}\right) \quad (4)$$

The PDF and CDF for the site are presented in Figs. 5 and 6, respectively.

2.3 PV system

The PV technology is an array of the PV cells connected in parallel or series for conversion of solar energy to electrical energy [5]. The power output of the PV system can be expressed as [11]

$$P_{\mathrm{PV}} = \eta_{\mathrm{pv}} \times A_{\mathrm{pv}} \times I_{\mathrm{pv}} \quad (5)$$

where η_{pv} is the PV module efficiency, I_{pv} is the solar irradiation (kWh/m^2) and A_{pv} is the surface area of the PV system (m^2). The daily and average monthly global radiations for the site are presented in Figs. 7 and 8.

The stochastic characteristic of solar irradiance at time t is modelled by using beta distribution function. The PDF of beta distribution, for $0 \le s(t) \le 1$ and shape parameters α, $\beta > 0$, is a function of the variable $s(t)$ and its reflection $(1 - s(t))$ [13]
(see (6))

$$B(\alpha, \beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha + \beta)} \quad (7)$$

where $s(t)$ is the solar irradiance (kW/m^2) and α and β are fitting parameters

$$\alpha = \mu\left\{\frac{\mu(1-\mu)}{\sigma^2} - 1\right\}, \quad \text{if } \sigma^2 < \mu(1-\mu) \quad (8)$$

$$\beta = \{1-\mu\}\left\{\frac{\mu(1-\mu)}{\sigma^2} - 1\right\}, \quad \text{if } \sigma^2 < \mu(1-\mu) \quad (9)$$

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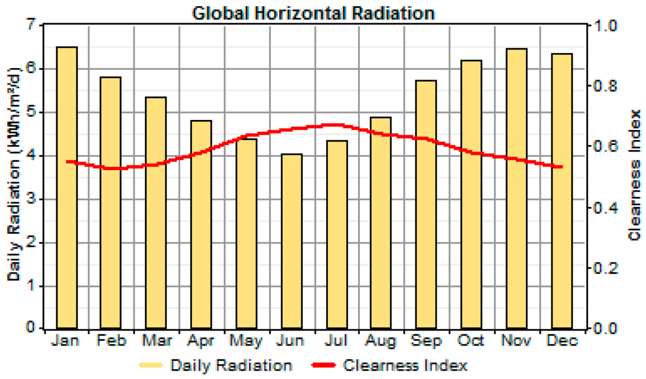

Fig. 7 *Daily radiation and cleanness index*

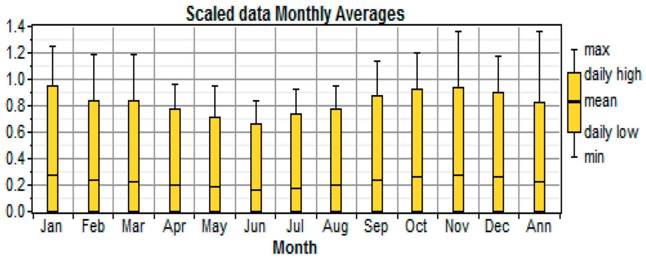

Fig. 8 *Monthly average radiation*

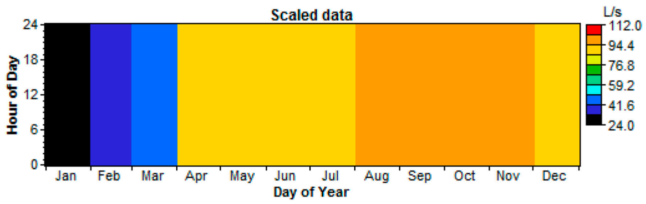

Fig. 9 *Daily variation of hourly mean water flow*

2.4 HT system

HT converts the kinetic energy in flowing water to electrical energy with the application of a dam, penstock and forebay. It operates with no environmental impacts based on the specifications of the manufacturers. The selection of a suitable HT for a specific application depends on the net head, variation of flow discharge, rotational speed, cost and so on. The power output of the HT can be expressed [14]

$$P_{\rm HT} = \eta_{\rm HT} \times \rho_{\rm water} \times g \times \psi_{\rm net} \times Q_{\rm turbine} \tag{10}$$

where $\eta_{\rm HT}$ is the efficiency, g is the acceleration due to gravity (m/s^2), $\rho_{\rm water}$ is the density of water (kg/m^3), $Q_{\rm turbine}$ is the flow rate (m^3/s) and $\psi_{\rm net}$ is the net head (m). The daily variation of hourly mean and monthly average water flow rate for the selected HT and site are presented in Figs. 9 and 10.

2.5 Battery storage system

A BSS is a process by which electricity imported from the RERs can be stored during the off-peak period when the power consumption is low and feedback into the power system at the peak load period when the power demand is high. The storage bank autonomy ($\text{SBA}_{\rm batt}$) is the ratio of the BSS size to the electric load. The $\text{SBA}_{\rm batt}$ of the battery can be estimated by using the following equation [14]:

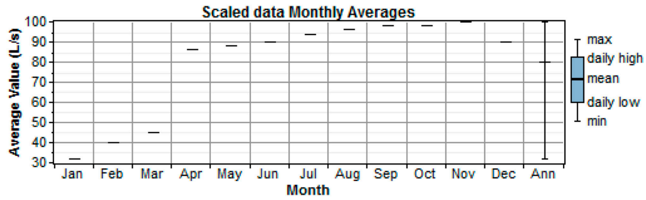

Fig. 10 *Monthly average water flow rate*

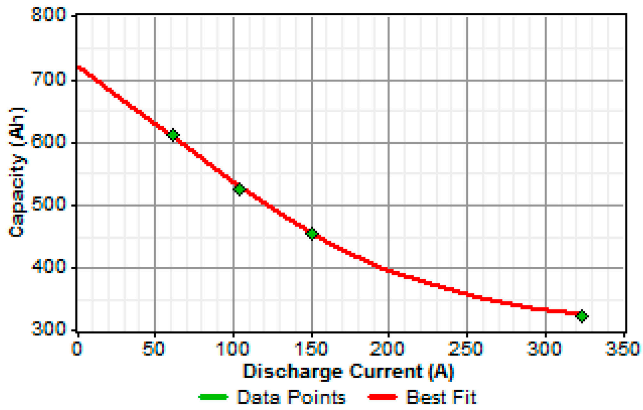

Fig. 11 *Efficiency of the batteries*

$$\text{SBA}_{\rm batt} = \frac{N_{\rm ess} V_n Q_n (1 - (q_{\rm min}/100))(24/d)}{P_{\rm prim,ave}(100\,\text{Wh/kWh})} \tag{11}$$

where V_n is the nominal voltage of a single BSS (V), $N_{\rm ess}$ is the number of BSSs in a bank, Q_n is the nominal capacity of a single BSS (Ah), $P_{\rm prim,ave}$ is the average primary load (kWh/d) and $q_{\rm min}$ is the minimum state of charge of the BSS bank (%). The BSS charge efficiency can be expressed as

$$\eta_{{\rm BSS},c} = \sqrt{\eta_{{\rm BSS},rt}} \tag{12}$$

where $\eta_{\rm BSS,c}$ is the BSS charge efficiency and $\eta_{\rm BSS,rt}$ is the BSS round trip efficiency.

The maximum BSS charge power in relation to the maximum charge current is given in (13) as [14]

$$P_{\rm BSS} = \frac{N_{\rm ess} \times I_{\rm max} \times V_n}{1000} \tag{13}$$

where $N_{\rm BSS}$ is the number of BSSs in the storage bank and $I_{\rm max}$ is the BSS maximum charge current (A). The efficiency of selected BSS is shown in Fig. 11.

2.6 Diesel generator

DG offers durable and reliable power solutions for residential, commercial and industrial applications. It can be used for power applications in rural areas because of its low initial costs and high efficiency. The fuel consumption rate of a DG can be expressed as [14]

$$F = F_0 \cdot Y_{\rm dg} + F_1 \cdot P_{\rm DG} \tag{14}$$

where F_0 is the fuel curve intercept coefficient (units/h/kW), F_1 is the fuel curve slope (units/h/kW) and $Y_{\rm dg}$ is the rated capacity of the DG (kW). The fuel consumption of the proposed DG is presented in Fig. 12.

$$f(s(t)) = \begin{cases} \dfrac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} s(t)^{\alpha-1}(1-s(t))^{\beta-1}, & \text{for } s(t) \in (0,1), \alpha \ge 0, \beta \ge 0 \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

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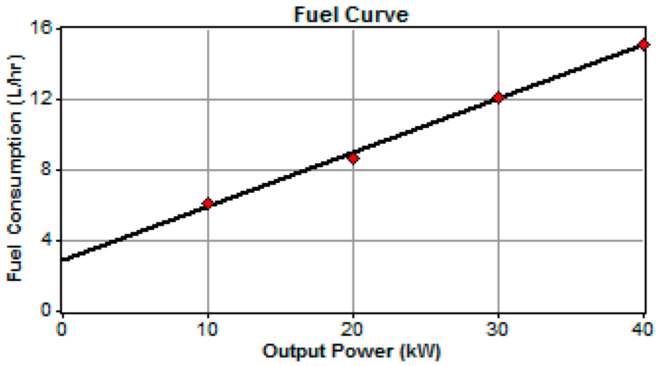

Fig. 12 *DG fuel consumption*

Table 1 Configuration of five case studies

S/N	Description	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5
1	diesel generator, kW	40	40	40	40	40
2	hydro turbine, kW	0	0	0	0	18.4
3	WTG, kW	0	10	0	10	10
4	PV, kW	0	0	10	10	10
5	BSS, kWh	0	0	32	32	32
6	inverter, kW	0	0	80	80	80

3 Modelling of the economic components of an MG

The techno-economic analysis of an MG system presented in this study is based on some operating parameters that are used for economic assessment of RERs in an MG system.

3.1 Annualised cost of the system

The ACS for each component of the system can be estimated by using (15) [3, 14]

$$\text{ACS} = \sum_{i=1}^{n} [\text{ACC} + \text{ARC} + \text{AMC} + \text{AFC} - S], \ \$/\text{yr} \qquad (15)$$

where ACC, AMC, AFC, ARC and S are the annualised capital cost, annualised maintenance cost, annualised fuel cost, annualised replacement cost and salvage value, respectively. The total ACS for the entire MG system can be expressed as [14]

$$\text{ACS}_{\text{total}} = \text{CRF}(i, P_{\text{proj}}) \times \text{NPC}_{\text{total}} \ \$/\text{yr} \qquad (16)$$

where i is the annual real discount rate (%), P_{proj} is the project lifetime (yr) and $\text{NPC}_{\text{total}}$ is the total NPC ($) and $\text{CRF}(i, P_{\text{proj}})$ is the capital recovery factor.

3.2 Salvage value

Salvage value is the estimated resale value of the power system component at the end of the project lifetime [14]

$$S = \text{RC}_{\text{rep}}\left(\frac{\text{RL}_{\text{rem}}}{\text{CL}_{\text{comp}}}\right) \qquad (17)$$

where (RL_{rem}) is the remaining life of the component at the end of the project lifetime, CL_{comp} is the lifetime of the component (yr) and RC_{rep} is the replacement cost of the component ($).

3.3 Capital recovery factor

The CRF of an MG system can be calculated with the application of real discount interest rate and life span of the system. The CRF for an MG system can be expressed as [3]

$$\text{CRF}(i, P_{\text{proj}}) = \frac{i \cdot (1+i)^{P_{\text{proj}}}}{(1+i)^{P_{\text{proj}}} - 1} \qquad (18)$$

3.4 Net present cost of an MG power system

The NPC for the whole system can be estimated by considering the ACS of each component of the system

$$\text{NPC}_{\text{total}} = \frac{\text{ACS}_{\text{total}}}{\text{CFR}}, \ \$/\text{yr} \qquad (19)$$

3.5 Cost of energy

The COE is mainly obtained from the ACS and AES of the system. It can be expressed as [3, 14]

$$\text{COE} = \frac{\text{ACS}_{\text{total}}}{\text{AES}} \qquad (20)$$

4 Results and discussions

The feasibility studies and performance evaluations of an MG system are implemented in this work by utilising the five scenarios and their configurations as presented in Table 1 based on their technical specifications.

4.1 Analysis of the results

The proposed MG system has been modelled to obtain an optimised configuration. In this research work, five case studies have been considered for supplying electric power to the study area having examined the optimisation of the available RERs. The feasibility of the contextual investigations is classified based the technical, environmental and economic results that are presented in Tables 2–4. The cost analysis and environmental assessment are used in this study to choose the best design among the various combinations of the MG system.

Case study 1: The share of energy generation from the DG is 225,515 kWh/yr, which is estimated to be 100% of the total energy demand as shown in Fig. 13*a*. This has a negative effect on the optimal operation of the MG system. The COE recorded in this scenario is the highest due to the fact that the ACS, fuel cost and operating costs are quite high when compared with the other case studies. It is also noticed that values of the GHG emissions as presented in Table 4 are more than other case studies, this has an

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Table 2 Technical analysis of five case studies

Description	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5
capital, $	20,000	21,200	33,400	34,600	41,600
NPC, $	1,628,787	1,571,885	1,449,089	1,559,087	942,654
operating cost, $/yr	125,850	121,305	119,349	113,658	70,487
COE, $/kWh	0.574	0.553	0.542	0.517	0.327
fuel consumption, L/yr	93,112	89,283	88,350	83,765	51,236
renewable fraction, %	0	0.06	0.07	0.13	0.5

Table 3 Economic assessment of five case studies

Case studies	ACC, $/yr	ARC, $/yr	AMC, $/yr	AFC, $/yr	Salvage, $/yr	ACS, $/yr
1	1565	8978	5255	111,734	−117	127,415
2	1658	9013	5275	107,140	−124	122,963
3	2613	8797	4871	106,020	−339	121,962
4	2707	8746	4807	100,519	−413	116,365
5	3254	5854	3350	61,848	−202	73,741

Table 4 Environmental assessment of five case studies

Pollutant	Emissions, kg/yr				
	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5
carbon dioxide	245,194	235,112	232,654	220,582	134,922
carbon monoxide	605	580	574	544	333
unburned hydrocarbons	67	64.3	63.6	60.3	36.9
particulate matter	45.6	43.7	43.3	41	25.1
sulphur dioxide	492	472	467	443	271
nitrogen oxides	54,000	5178	5124	4858	2972

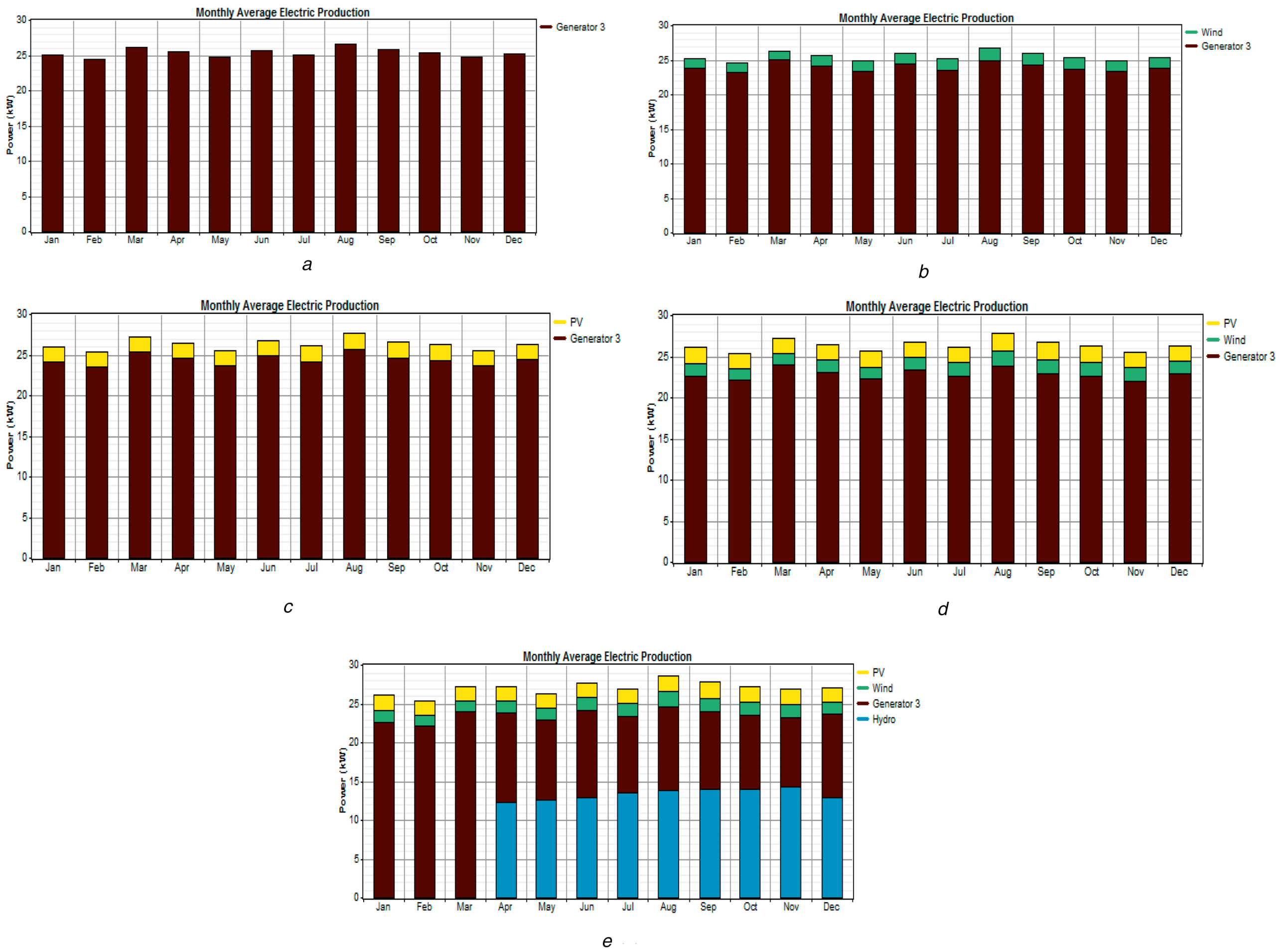

Fig. 13 *Share of electrical energy generation for each component of an MG system for*
(a) Case study 1, ***(b)*** Case study 2, ***(c)*** Case study 3, ***(d)*** Case study 4 and ***(e)*** Case study 5

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environmental implication on the MG system. This indicates that the operation of a DG to meet the load demand of a standalone system is not economically and environmentally feasible.

Case study 2: Case 2 study as shown in Fig. 13*b* demonstrates that DG and WTG contribute 210,026 and 13,866 kWh/yr to the total energy demand. This has reduced the values COE, NPC, fuel consumption and ACS considerably by 3.7, 3.5, 4.1 and 3.5%, respectively. The penetration of WTG into the MG system has marginally reduced the values of the aforementioned operating parameters. However, a lower renewable fraction has made the configuration to be very less. The contribution of WTG is not very significant, as it only contributes 6% of the total energy produced, whereas energy generated from the DG is 94%. This indicates that WTG is not a good option in the site due to the intermittent nature of wind speed. In addition to this, the O&M of the WTG and BSS should be taken into consideration. The simulation results established the fact that this case study is not cost effective based on some KPIs.

Case study 3: Case 3 as presented in Fig. 13*c* shows that power generation from the DG source has reduced slightly. In this scenario, the energy share of the DG is 214,003 kWh/yr and PV is 16,856 kWh/yr. This indicates that the DG and PV have contributed 93 and 7% to the total energy demand at the load points. This has reduced the COE, NPC, fuel consumption and ACS by 5.6, 11, 5.1 and 4.3%, respectively. The results presented in Table 4 show that the MG produces a lesser GHG emission in this scenario when compared with case study 1. This case study is not economically favourable due to the high values of ACS, NPC, fuel consumption and lower value of RERs penetration. However, this case study performs better than the base case study in terms of GHG fuel consumption, NPC and ACS reduction and energy sharing.

Case study 4: The impacts of the PV and WTG on the operation of an MG system are investigated in this case study. Based on the intermittent nature of wind and solar resources, the qualities of one source can be utilised by the utilities to surmount the shortcomings of other sources. The energy share of each component of the MG is as follows: DG is 200,354 kWh/yr, PV is 16,856 kWh/yr and WTG is 13,866 kWh/yr as presented in Fig. 13*d*. The results obtained in case study 4 show that the DG produces 87% of the energy demand while the PV and WTG contribute 7 and 6%. The increase in the renewable energy fraction significantly reduces the COE, NPC, fuel consumption and ACS by 9.9, 11, 10 and 8.7%, respectively. Although the values of the GHG emissions and some KPIs have reduced, the lower renewable fraction makes the configuration to be unfavourable.

Case study 5: Case study 5 as shown in Fig. 13*e* proves that the energy contribution of the DG has reduced significantly with the application of HT. In this scenario, the energy share of DG is 117,987 kWh/yr and PV, WTG and HT are 16,856, 13,866 and 117,987, respectively. The percentage of energy share shows that DG, PV, WTG and HT have contributed 50, 7, 6 and 37%, respectively, of the energy requirements of consumers. The utilisation of HT is significant in this case study and has contributed to optimal operation of an MG system. This has reduced the values of COE, NPC, fuel consumption and ACS by 43, 42.1, 45 and 42.1%, respectively. This case study has been found to be the optimised configuration and solution based on results got from the simulation.

The five case studies are compared on the basis of some KPIs and the results obtained from the comparison demonstrate that case study 5 is the best configuration to meet the load requirements of an MG system. The values of NPC and operating costs for this case study are $94,265.4 and $70,487, which are estimated to be 45 and 44% lower than the case study 1. The system has a capital cost of $41,600 which is estimated to be higher than the other case studies because of the higher cost of HT. From Table 4, it is evident that the GHG emissions are lower than the other case studies. The reason behind this, is because of the higher penetration of RERs which results in 50% of total energy delivered. Moreover, the configuration is economically viable with a COE of $0.327/kWh and the ACS of $73,741/yr that are estimated to be the smallest among the five case studies.

5 Conclusion

The research work investigates the benefits of utilising RERs in an MG by comparing the results obtained with the base case simulation. The results obtained from the analysis suggested that case study 5 is more economically and environmentally viable in view of the operating costs, fuel consumption, ACS, NPC, COE and GHG emissions. This has established the fact that RERs are promising solutions to meet the power requirements of the remote areas. These results have justified that the utilisation of RERs in an MG system reduces over-dependence on the limited fossil fuels for power generation. For this reason, the power utilities and decision makers can utilise the results obtained from this study in real time to make a good choice to reduce the operating cost of a power system. The technique adopted in this research work can serve as a reference for rural electrification projects and to solve socioeconomic problems associated with power system.

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