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Economic and environmental analysis of a co-generation power system with the incorporation of renewable energy resources

T. Adefarati[a], R.C. Bansal*[b, a]

[a]*Department of Electrical, Electronic and Computer Engineering, University of Pretoria, South Africa*
[b]*Department of Electrical and Computer Engineering, University of Sharjah, United Arab Emirates*

Abstract

Combined heat and power is utilized to generate electric power and produce thermal energy for various applications. In view of this, we investigate the economic savings and environmental effects of using a co-generation system that is made-up of microturbine (MT) and other auxiliaries instead of using only a gas boiler. This paper addresses the power-scheduling problem among the generating units in a microgrid (MG) system that comprises of photovoltaic (PV), wind turbine generator (WTG), MT, grid and battery storage system (BSS). The optimal operation of the proposed MG system is obtained by considering the demand response, operating costs and other key performance indicators. The objective function of this study is to minimize the cost of energy, NPC, emission, operating cost, fuel cost and grid energy purchase. HOMER software is utilized to accomplish the goal of the research work. In this paper, a model is developed to investigate the performances of the system having considered the economic and environmental significance of utilizing renewable energy resources (RERs) in a MG system. The results of the simulation analysis reveal that the proposed model is cost effective to reduce the operating costs of the MG system with the application of RERs.

Keywords: Annaulised cost of the system; boiler; cost of energy; fuel cost; microgrid; renewable energy resources.

1. Introduction

The application of the fossil fuels as the primary sources of power generation has resulted in environmental degradation and ozone layer depletion [1]. Owing to this, economic and environmental impacts of fossil fuels on the operation of a power system deserve new sources of energy that are substantially available, non-depleting, sustainable and environmentally friendly and can improve the efficiency of a power system [2]. The unique

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characteristics of RERs have encouraged their applications as measures to improve the global electric power generation. The availability of RERs such as solar and wind energy offer many opportunities for the utilities for the development of sustainable energy for their numerous customers [3]. Hence, the application of RERs in the MG systems can be effectively utilized to enhance the economic efficiency of power system operation [4]. A MG system with the integration of multiple sources has turned out to be the cost effective power solutions to meet the power demand and thermal energy requirements of the consumers. Owing to the fact that the combination of a numerous power sources can be used as a measure to complement each other and overcome their various setbacks, this will ultimately result in a higher energy conversion efficiency [5], [6]. The utilization of a CHP in a power system can be effectively utilized to enhance the power system efficiency when compared with a conventional generating unit that does not use a heat recovery. This reduces the operating cost when compared to purchasing or generating electricity and heat energy in a separate system.

Apart from the power generation system, various MG systems have been proposed for CHP applications recently. Ye et al. [7] have proposed a dispatch model to minimize the operating cost of a MG system. Whereas, Choi et al. [8] have proposed an energy management system with the application of a hybrid energy storage system for a minimization of energy loss and battery current fluctuation. The aforementioned literature review reveals that MT, PV, WTG, grid and BSS sources have not been fully employed to generate electricity and provide the required thermal energy for various applications. In the present work, MT coupled with RERs and BSS are proposed to optimize the grid energy purchase, NPC, COE, fuel cost, emission and operating cost. The performance of the proposed power system is evaluated by comparing the different configurations of the MG system. This is accomplished by carrying out the environmental and economic assessment to detect the best configuration based on the objective function of the study. The results obtained from this work reveal the effectiveness of using RERs in a MG power system.

Nomenclature

ACS	Annualized cost of system ($/yr)	COE	Cost of energy ($/kWh)
AEP	Annual energy production (kWh/yr)	CHP	Combined heat and power
CRF	Capital recovery factor	GHG	Greenhouse gas emission
C_{grid}	Energy purchase from the grid	C_{fuel}	Fuel cost
C_o	Operating cost ($/yr)	η_{boiler}	Boiler efficiency
B^t_{fc}	Fuel consumption of the gas boiler at time t	F_{price}	Fuel price
P^t_{elec}	Price of electricity purchase from the grid at time t	GHG_{em}	Greenhouse gas emissions
P^t_{grid}	Quantity of electricity purchase from the grid at time t	MT^t_{fc}	Fuel consumption of the MT at time t
η_{mt}	Efficiency of a microturbine	η_{mt}	Efficiency of a microturbine
$P_{mt\ (elect)}$	Net electrical power output of a MT	$P_{mt\ (therm)}$	Thermal power recovered from a MT
FH_r	Lower heating rate of the fuel (kJ/kgf)	mf_r	Mass flow of gas (kg/s)
LHV_{fuel}	Lower heating value of the fuel (MJ/kg)	$c_{fuel;eff}$	Effective price of the fuel ($/kg)
HRF	Heat recovery facility	NPC	Net present cost

2. Objective function

The objective function of the study is to minimize the COE, fuel cost, operating cost, NPC, energy purchase from the grid and emission. The objective function of the MG system is expressed in eq. (1) as:

$$F = \min \sum_{i=1}^{n} \{GHG_{em} + C_{fuel} + C_o + COE + NPC + C_{grid}\} \tag{1}$$

The electricity purchase from the grid is presented in eq. (2) as:

$$C_{grid} = \sum_{i=1}^{n} P^t_{elec} P^t_{grid} \Delta t \tag{2}$$

The cost of fuel consumed by the gas boiler and microturbine can be expressed as:

$$C_{fuel} = F_{price} \sum_{i=1}^{n} \left(B^{t}{}_{fc} + MT^{t}{}_{fc} \right) \tag{3}$$

The cost of the energy from the proposed MG system can be expressed as:

$$COE = \frac{ACS}{AEP} \quad (\$/\text{kWh}) \tag{4}$$

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

$$NPC_{total} = \frac{ACS_{total}}{CRF} \quad (\$/\text{yr}) \tag{5}$$

Power system balance based on the operating limits of the MG system is presented in eq. (5) as:

$$\sum_{i=1}^{n} P_{Di} = \sum_{i=1}^{n} P_{PV,i} + \sum_{i=1}^{n} P_{WTG,i} + \sum_{i=1}^{n} P_{MT,i} \pm \sum_{i=1}^{n} P_{BSS,i} + \sum_{i=1}^{n} P_{grid,i} \tag{6}$$

3. Microgrid system

A MG is a small-scale power system that consists of a number of distributed energy sources as presented in Fig. 1. It can be effectively incorporated with numerous sources of distributed generation technologies to meet the power demand and thermal energy of the consumers. The proposed MG system is designed for the generation of electricity and thermal energy of the consumers owing to the availability of the local RERs. The proposed model is validated by utilizing a number of case studies based on the meteorological data of De Aar, a town that is located in South Africa.

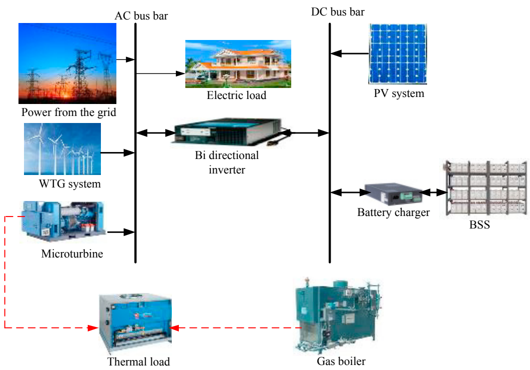

Fig. 1. A CHP microgrid power system

3.1. Microturbine

Microturbine is a new technology that burns gaseous and liquid fuels to create high-speed rotation that turns an alternator attached to the shaft of the engine for power generation and thermal energy production. It can be utilized for small and medium sized energy applications because of its operating characteristics such as low emission and low O&M cost. A lot of money can be saved by utilizing MTs to generate electricity and produce thermal energy for various applications. This indicates that the operation of MTs can reduce the operating cost of producing electricity at a cheaper cost than to purchase from the utilities. The efficiency of a MT can be expressed as [9]:

$$\eta_{mt} = \frac{P_{mt}(elect) + P_{mt}(therm)}{mf_r \times FH_r} \tag{7}$$

The fuel cost of a microturbine can be expressed as [9]:

$$FC_{mt} = PNG\sum_{k}^{n}\frac{P_k}{\eta_k} \tag{8}$$

where FC_{mt} is the fuel cost of a microturbine, PNG is the price of natural gas, P_k is the electrical power generated at interval k and η_k is the cell efficiency at interval k.

3.2. Boiler

The boiler is a device that uses multiple fuels for production of thermal energy. It is designed by the manufacturer to provide an unlimited amount of thermal energy on demand. The operation of the MG system allows the waste heat recovered from the MT to be utilized for the generation of electricity. This indicates that the boiler is mainly utilized to serve any thermal load that the MT cannot meet. The marginal cost of a boiler is presented as [10]:

$$C_{boiler,mar} = \frac{3.6c_{fuel,eff}}{\eta_{boiler}LHV_{fuel}} \tag{9}$$

4. Configuration and technical specifications of the MG system

The configuration and technical specifications for the proposed MG system are presented in Table 1. This data is utilized to evaluate the economic and environmental viability of a co-generation system.

Table 1. Configuration of the case studies and technical data the proposed MG system.

Case studies	MT	Grid	Boiler	Heat recovery	PV	WTG	BSS
1	✓	✓	✓	×	×	×	×
2	✓	✓	✓	✓	×	×	×
3	✓	✓	✓	✓	✓	✓	✓
Technical data	60 kW	20 kW	Efficiency = 85%		10 kW	10 kW	1,900 Ah (7.6 kWh)

5. Results and discussions

In this research work, a MG consists of thermal load and electrical load. According to the results of environmental and economic assessment, the simulation analysis of each case study are presented in this section. The electrical load and thermal load profile of the MG operation is illustrated in Fig 2.

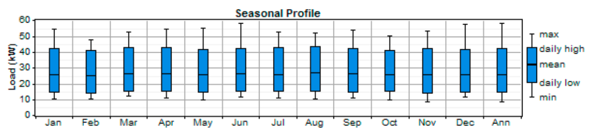

Fig. 2a. Seasonal electrical load

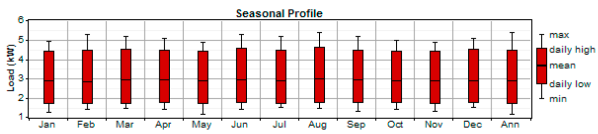

Fig. 2b. Seasonal thermal load

Case study 1: The power and heat energy requirements are met with the application of the MT, grid and gas boiler without using HRF, PV, WTG and BSS. The energy purshased from the grid for each case study on monthly basis is presented in Table 2 where the share of electricity from the MT and grid and the key operating parameters are presented in Table 3. This shows that 86% of the electricity requirement comes from the MT while 14% is obtained from the grid. In this case study, boiler produces 100% of the thermal energy required by the consumers. The values of emissions from the MT and boiler as presented in Table 4 are too high owing to the absence of HRF and RERs.

Case study 2: The case study 1 is upgraded with the integration of the HRF. The application of the HRF in the MG allows the thermal load of the consumers to be shared between the boiler and MT. This indicates that unmet thermal energy from the boiler can be balanced with application of the MT through a HRF. The energy share in this scenario indicates that 6% of the electricity is purchased from the grid while the 94% is sourced from the MT as shown in Table 3. The application of the HRF has reduced the values of GHG emissions as presented in Table 4.

Case study 3: This case study is the same with the case study 2 with the incorporation of PV, WTG and BSS. The electricity production from the PV, WTG, MT and grid purchase is presented in Table 3 and Fig. 3a. This indicates that 4.6%, 2.94%, 88.94% and 3.52% of the total electricity production comes from the aforementioned sources. The thermal energy production from the boiler is 10%, while 90% of thermal energy comes from the MT. The integration of RERs and BSS into the MG system has reduced the operating cost of the system as shown in Table 3. Also, the results obtained from this case study have proved that the incorporation of additional units of RERs and ESS in a MG system have reduced GHG emissions as presented in Table 4. The ACS and NPC based on each component that constitutes the MG system for case study 3 is presented in Fig. 4.

Table 2. Energy purshased from the grid.

Energy purshased from the grid (kWh)			
Month	Case study 1	Case study 2	Case study 3
Jan	4,741	2,292	1,219
Feb	4,248	1,870	875
Mar	4,032	1,765	1,216
Apr	4,042	1,753	1,189
May	4,536	2,229	1,121
Jun	4,236	1,976	1,175
Jul	4,277	2,078	1,201
Aug	3,689	1,831	1,347
Sep	4,012	1,842	1,143
Oct	3,955	1,545	1,094
Nov	4,456	2,219	1,072
Dec	4,075	2,016	1,105
Annual	50,300	23,415	13,758

Table 3. Economic analysis of the MG system.

Description	Case study 1	Case study 2	Case study 3
Fuel consumption (m^3/yr)	229,822	188,004	184,176
Fuel cost ($/yr)	22,982	18,800	18,418
Electricity purchased from the grid ($/yr)	6,023	2810	1,651
Operating cost ($/yr.)	42,247	36,196	35,042
NPC ($)	505,976	478,060	441,379
COE ($/kWh)	0.112	0.104	0.095
Share of electricity (kWh/yr)	Grid = 50,300	Grid = 23, 415	Grid = 13, 758
	MT = 318,108	MT = 351,840	MT = 347, 710
	PV= 0	PV= 0	PV= 17,983
	WTG = 0	WTG = 0	WTG = 11, 498
Excess electricity (kWh/yr)	3,409	10,257	3,664
Thermal energy (kWh/yr)	Boiler = 547,499	Boiler = 31,322	Boiler = 76,058
	MT= 0	MT= 733,924	MT= 690,778
Excess thermal energy (kWh/yr)	0	217,747	219,337

Table 4. GHG emissions for the three case studies.

Pollutants	Emission (kg/yr)		
	Case study 1	Case study 2	Case stydy 3
Carbon dioxide	493,674	385,800	368,857
Carbon monoxide	1,494	1,222	1,197
Unburned hydrocarbons	165	135	133
Particulate matter	113	92.1	90.2
Sulfur dioxide	1,309	1,022	976
Nitrogen oxides	13,397	10,936	10,701

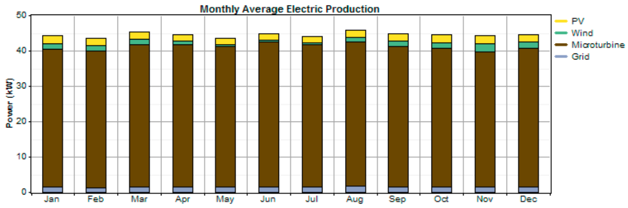

Fig. 3a. Electric energy from diferent sources

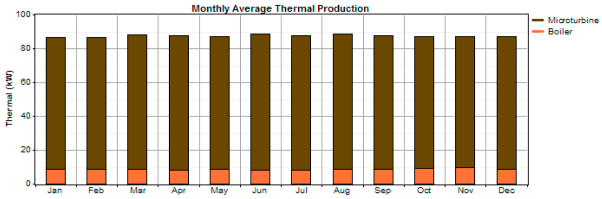

Fig. 3b. Thermal energy from diferent sources

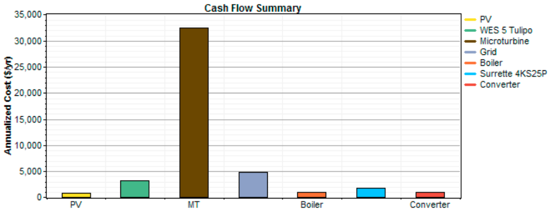

Fig. 4a. Annualized cost of the system

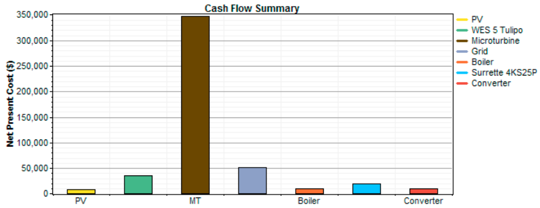

Fig. 4b. Net present cost of the system

6. Conclusions

The research work has provided vital information to enhance the efficiency of a co-generation power system at minimum operating cost and cost of energy. This work investigates a situation where the consumers purchase gas from the utilities to serve both electrical and thermal loads. The production of electric and thermal energy from the proposed MG can be utilized to reduce the operating cost, COE, emission, NPC, energy purchase from the grid and gas consumption. The model adopted in this work can help the utilities to understand the concept and benefits of RERs and economic analysis of the CHP system. The results obtained from the study show that the utilities can save a lot of money by using MT, PV, WTG and BSS to produce electricity and thermal energy.

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Biography

Prof. Ramesh Bansal has over 25 years of experience and currently he is Professor and head of the department in the Department of Electrical and Computer Engineering at University of Sharjah. He has published over 300 papers. Prof. Bansal is an Editor/Associate editor of IEEE Systems Journal, IET-RPG & Electric Power Components and Systems. He is a Fellow and CEngg IET-UK, Fellow Engineers Australia and Institution of Engineers (India) and Senior Member-IEEE.