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# TECHNO-ECONOMIC EVALUATION OF A GRID CONNECTED MICROGRID-COGENERATION SYSTEM USING WIND TURBINES, MICROTURBINE AND BATTERY SYSTEM

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**ABSTRACT**

The application of the WT, BSS and MT in the utility grid requires a new algorithm for proper management of a MG system. The proposed MG system is designed with a model to supply the thermal and electrical energy through a grid-connected power system and to evaluate the techno-economic impacts of RETs in a power system. In this study, a new methodology for optimal operation of a CHP is considered based on the stochastic characteristics of wind resources, thermal and power demands. The model is developed owing to hourly energy supply that can satisfy the electrical and thermal requirements with minimum ATC. The WT is utilized in conjunction with HOMER application software to evaluate the economic benefits of RETs. The results obtained from the investigation show that the utilization of a grid-connected MG CHP minimizes the ATC of the power system.

**Keywords:** battery storage system, economic, environment, wind turbine, wind speed

**NONMENCLATURE**

*Abbreviations*

| | |
|---|---|
| *ATC* | Annual total cost |
| BSS | Battery storage system |
| CHP | Combined heat and power |
| *CV* | Gross calorific value (kcal/kg) |
| KPIs | key performance indicators |
| MG | Microgrid |
| *MT* | Microturbine |
| *PNG* | Price of natural gas |
| RETs | Renewable energy technologies |
| *SOC* | State of charge |
| *T&D* | Transmission and distribution |
| *WT* | Wind turbine |

*Symbols*

| | |
|---|---|
| $ACS_{c,i}$ | Annualized cost of the system |
| *a, b, c, d* | fitting parameters from the data sheet |
| $C_{g,k}$ | Energy charge by the utility |
| $C_{p,k}$ | Cost of energy purchased from the grid |
| $C_{s,k}$ | Cost of energy sold to the grid in the month *i* with the rate k (R/kWh) |
| $D_A$ | Battery autonomy |
| $DOD_{max}$ | Maximum battery depth of discharge |
| $EC_{gp,i,j}$ | Amount of energy purchased from the grid in month *j* during the time rate *i* (R/kWh) |
| $EC_{gs,i,j}$ | Amount of energy sold to the grid in month *j* during the time rate i (R/kWh) |
| $E_{gen}(t)$ | Energy produced by the WT at time *t* |
| $E_{g,i}$ | Energy purchase from the grid without the utilization of MT and WT units |
| $E_{L(Ah)}$ | Load consumption (Ah) |
| $E_{load}(t)$ | Energy demand |
| $E_{p,i}$ | Energy purchased |
| $E_{s,i}$ | Energy sold in the month *i* (kWh) |
| $FC_{mt}$ | Fuel cost of a MT |
| $FH_r$ | Lower heating rate of the fuel (kJ/kgf) |
| $H_{ess}$ | Enthalpy of saturated steam (kcal/kg) |
| $H_{efw}$ | Entropy of feed water (kcal/kg) |
| $H_{out}$ | Amount of recovered heat |
| $\eta_{bat}$ | BSS efficiency |
| $\eta_{inv}$ | Inverter efficiency |
| $\eta_k$ | Cell efficiency at interval *k* |

| | |
|---|---|
| $\eta_{mt}$ | *E*fficiency of a MT |
| $\eta_{temp}$ | *B*attery temperature correction factor |
| $N$ | *N*umber of months |
| $mf_r$ | *M*ass flow of gas (kg/s) |
| $P_{grid,i}$ | *G*rid power for rate *i* (R/kWh) |
| $P_k$ | Electrical power produced at interval k |
| $P_{mt}$(elect) | Net electrical power generated by a MT |
| $P_{mt}$(therm) | Thermal power recovered from a MT |
| $P_{out}$ | Power output of MT |
| $P_{rated}$ | Rated power |
| $P_{sb,i}$ | *S*ellback rate *i* (R/kWh) |
| $q$ | Rate of fuel used (kg/h) |
| $Q_{steam}$ | *R*ate of steam flow (kg/h) |
| $S_i$ | *S*alvage value of the components |
| *SOC (t)* | BSS at the initial of interval *t* |
| *SOC (t-1)* | BSS at the end of interval *t* |
| $v_{co}$, $v_{ci}$ and $v_r$ | cut-out, cut-in and rated wind speeds |
| $\sigma$ | *S*elf-discharge factor |

## 1. INTRODUCTION

A microgrid system is a combination of the WT, BSS and MT for simultaneouse provision of thermal and electrical energy to various consumers at load centres. The grid-connected MG CHP system offers high efficiency, environmental, economic and reliability benefits compared to a conventional generating unit that only produces the electrical energy [1]. The CHP is a cost-effective system which can be installed quickly with little geographical constraints. Apart from this, it can utilize the variety of fuels for industrial, residential and commercial applications [2]. The CHP systems are generally designed by the utilities to provide efficient electricity and thermal energy for industrial processing applications [3].

The renewable energy is a clean and natural replenish source that can compete with conventional technologies [4]. It can be deployed in a power system to overcome climate change issue and reduce its detrimental effects that are associated with the operation of fossil fuel based generating unit [5]. Recently, there is a considerable shift from the conventional power technologies to RETs owing to techno-economic benefits [6]. The integration of BSS and WTs into a grid-connected MG system is a measure to maximize the benefits of RETs in a traditional power system. The design and operation of a MG system should take into consideration some operational strategies to improve the performance of a traditional power system [7]. The utilization of the WT is economically feasible in the circumstances where the wind speed is available based on the specifications of the manufactures [8]. The MT should be used in conjunction with the RETs and BSS in a place where thermal energy and electricity are required at low operating costs. In view of this, it is imperative to strategically design a MG system by considering deployment of the RETs into the grid power system based on the financial and technical benefits.

In the field of a MG system, many studies have been carried out by numerous scholars on the RETs and BSS for off-grid and grid-connected power solutions. Sawle et al. [9] have proposed particle swarm optimization and genetic algorithm techniques for minimization of cost of energy of a PV/wind/biomass MG system. Alalwan et al. [10] have presented a technique for sizing of a wind/PV/BSS MG system. The authors have presented the modeling and economic evaluation of a Wind-PV-BSS-diesel generator-biomass MG system. Based on the information that is available to the knowledge of the authors, little works have been done on the optimization of a MG system that comprises of RETs, MT and BSS.

This paper presents the HOMER application tool to achieve the objective of the study due to the fact that it can determine the optimal configuration to improve the energy efficiency. The optimal configuration of a MG system can be obtained by choosing the most suitable approach. There are some application tools such as PSCAD, ETAP and Digsilent Powerfactory that can be used for assessment of the MG systems, but due to some technical limitations, they are not suitable for optimization of a CHP system [11]. In this paper, HOMER has been used to optimize the annual total cost that consists of net energy purchased, annualized cost of the system and annual utility bill savings. The results obtained from this study can be used as prerequisites for power system reform of any country.

## 2. CONFIGURATION AND MODELING OF A MICROGRID SYSTEM

The components of a microgrid system explained in this section are as follows:

### *2.1 Description of a microgrid system*

A MG is a small-medium scale power system that comprises of loads, storage system and generating units and capable to operate in parallel with or independent of the utility grid. A typical MG system that consists of WT, BSS, MT and boiler is presented in Fig. 1. The proposed MG system supplies both thermal and electrical energy to the residential customers. The buildings that are powered with a microgrid system can generate revenue by exporting excess power to the grid and reduce congestion of the T&D lines. The thermal and electrical load profile for the proposed MG system is presented in Fig. 2, while the major components of the CHP system are shown in Fig. 3.

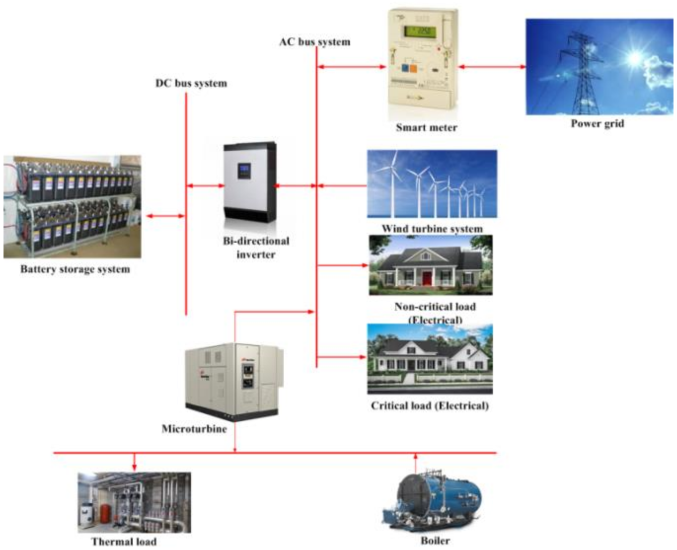


Fig.1. The proposed MG system

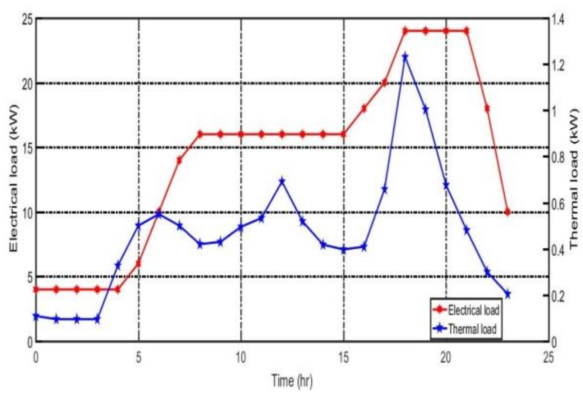


Fig. 2 Electrical and thermal load profile of the proposed MG system

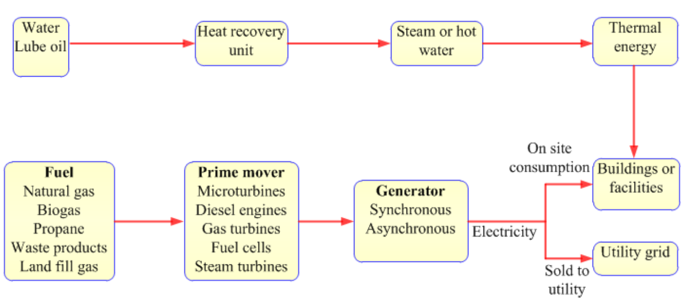


Fig. 3 The components of CHP technology

## 2.2 Wind turbine

A WT is a generating unit that changes the kinetic energy in the wind into electrical energy [4]. The monthly average wind speed for the selected site is presented in Fig. 4. It is observed from the figure that wind speed changes periodically (seasonally). The maximum wind speed for the site is obtained in July, at this particular time, the performance of the WT is impressive owing to a high generation of electrical energy and capacity factor. The average annual wind speed for the site is 6.39 m/s. The power produced by the WT can be computed as follows:

$$\begin{cases} P_{wt} = 0 & v < v_{ci} \\ P_{wt} = av^3 + bv^2 + cv + d & v_{ci} \le v \le v_r \\ P_{wt} = P_{rated} & v_r \le v \le v_{co} \\ P_{wt} = o & v > v_{co} \end{cases} \quad (1)$$

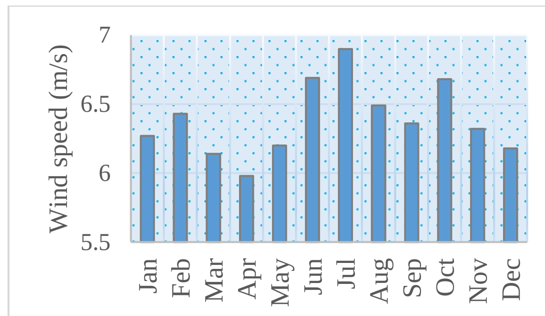


Fig. 4 Average monthly wind speed for Cape Town, South Africa

## 2.3 Battery storage system

The BSS comprises of strings of batteries that are connected in parallel or series or both for the purpose of smoothing out the effects of stochastic characteristics of RETs [12]. A lead acid battery is used in this study since it is cost-effective, reliable and robust. The required battery storage capacity $B_{cap}$ (Ah) can be expressed as [9], [13]:

$$B_{cap} = \frac{E_{L(Ah)} D_A}{DOD_{\max} \eta_{temp}} \quad (2)$$

The SOC can be used to estimate the residual capacity of the BSS. The SOC of the BSS during charging and discharging can be presented as follows [14]:

During charging

$$SOC(t) = SOC(t-1)(1-\sigma) + \left[ \frac{E_{gen}(t) - E_{load}(t)}{\eta_{inv}} \right] \times \eta_{bat} \quad (3)$$

During discharging

$$SOC(t) = SOC(t-1)(1-\sigma) + \left[\frac{E_{load}(t)}{\eta_{inv}} - E_{gen}(t)\right] \times \eta_{bat} \quad (4)$$

### *2.4 Microturbine*

A MT is a distributed generation technology that can be used in a relatively small-scale MG system for production of efficient and clean power and thermal energy. It is compact in size with a small number of moving parts and uses waste fuels with the application of waste heat recovery (WHR) facility. The efficiency of a MT is presented in equqtion (5) as [15]:

$$\eta_{mt} = \frac{P_{mt}(elect) + P_{mt}(therm)}{mf_r \times FH_r} \quad (5)$$

The fuel cost of a MT is presented in equation (6) as [15]:

$$FC_{mt} = PNG \sum_{k}^{n} \frac{P_k}{\eta_k} \quad (6)$$

The ratio of generated heat to electrical power in a MT can be determined with the application of heat to power ratio ($HP_{ratio}$). The $HP_{ratio}$ and fuel consumption of a typical MT depend on the step loading as shown in Fig. 5. The $HP_{ratio}$ can be expressed as [11]:

$$HP_{ratio} = \frac{H_{out}}{P_{out}} \quad (7)$$

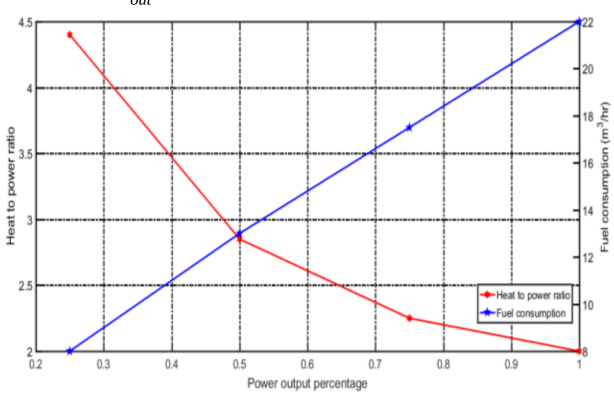


Fig.5. Fuel consumption and heat to power ratio of typical MT

### *2.5 Boiler system*

A boiler is a heat source for generation of steam or heated fluid for domestic and industrial applications. In a MG system, a boiler is a source that can produce thermal energy whenever necessary. The efficiency of boiler is presented in equation (8) as [16]:

$$\eta_{boiler} = \frac{Q_{steam}(H_{ess} - H_{efw})}{q \times CV} \quad (8)$$

## 3. OPTMIZATION MODEL

The proposed MG system is designed to minimize ATC of the system based on hourly energy demand. The ATC of the system consists of net energy purchased ($EC_{ge,\ i}$), annual utility bill savings ($U_{s,i}$) and the annualized cost of the system (ACS). The objective function of the study is represented in equation (9) as:

$$ATC_i = \min \sum_{i=1}^{n} \left(EC_{ge,i} + ACS_i - U_{s,i}\right) \quad (9)$$

The net energy purchased can be expressed by using equation (10) [17]:

$$EC_{ge} = \sum_{i}^{rates} \sum_{j}^{12} EC_{gp,i,j} \times P_{grid,i} - \sum_{i}^{rates} \sum_{j}^{12} EC_{gs,i,j} \times P_{sb,i} \quad (10)$$

The annual utility bill savings are the electricity cost savings due to the utilization of the WT, BSS and MT in a MG system.

$$U_s = \left\{ \left( \sum_{k=1}^{rate} \sum_{i=1}^{n} E_{g,i} \times C_{g,k} \right) - \left( \sum_{k=1}^{rate} \sum_{i=1}^{n} E_{p,i} \times C_{p,k} - \sum_{k=1}^{rate} \sum_{i=1}^{n} E_{s,i} \times C_{s,k} \right) \right\} \quad (11)$$

The ACS is a summation of the annualized capital and operation and maintenance costs of a renewable energy project minus the salvage value [17].

$$ACS = \sum_{i=1}^{n} \left(ACS_{c,i} - S_i\right) \quad (12)$$

## 4. OPTIMIZATION TECHNIQUE OF THE PROPOSED MG SYSTEM

A MG system that is structured to meet the thermal and electricity demand of typical consumers in Cape Town, South Africa is utilized in the study. The objective of the research work is to reduce the value of ATC that depends on the penetration level of wind resources, fuel cost, capacity of the battery used, capacity factor of the WT power output, average wind speed of the site, average power output of the WT, etc. The technical details to determine the financial feasibility of a MG system are shown in Table 1 [7], [8].

Table I Technical details of the proposed MG system

| | WT | BSS | Inverter | MT |
|---|---|---|---|---|
| lifetime | 20 years | 5 years | 15 years | 40,000 hrs |
| Rated Capacity | (3x5) 15 kW | 1 kWh | 10 kW | 30 kW |
| Cut-in speed | 2.7 m/s | Initial SOC = 90% | η=85% | Fuel=Natural gas |
| Rated wind speed | 11 m/s | Min SOC = 40% | - | Density = 0.790 kg/m³ |
| Cut-out speed | 25 m/s | max capacity= 513 Ah | - | - |
| Swept Area | 21.4 m² | - | - | - |

## 5. RESULTS AND DISCUSSIONS

The performance of a MG system is examined in this section by utilizing case studies with the application of the MT, WT and BSS. The MG system configurations are categorized based on the general results that are summarized in Table 2. The outcomes of the research work are presented as follows:

Case study 1: In this case study, the power system consists of a boiler that produces the thermal energy that is estimated to be 4,109 kWh/yr. After simulation of a MG system as described in Section 2.1, it can be seen that power supply from the utility grid is 120,772 kWh per annum which is 100% of the entire load at 1.09 R/kWh cost of energy. The results presented in Table 2 show that consumers depend on the power supply from the grid that is not economically feasible based on the high values of energy purchased, energy sold, net energy purchased, annual utility bill savings, energy charge and ACS. The values of the aforementioned KPIs are very high in this case study owing to the absence of RETs and MT penetration into the proposed MG system. The utility monthly summary for case study 1 is presented in Table 3.

Table 2 Overall results from different case studies

| Case Study | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Annual utility bill savings (R) | Energy charge (R ) | ACS (R) |
|---|---|---|---|---|---|---|
| 1 | 120772 | 0 | 120772 | 0 | 131859 | 132193 |
| 2 | 1501 | 1,458 | 42.2 | 131617 | 241.67 | 46,116 |

Table 3 Utility monthly summary for case study 1

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy charge (R) |
|---|---|---|---|---|
| January | 10,171 | 0 | 10,177 | 11,112 |
| February | 9,022 | 0 | 9,022 | 9,851 |
| March | 10,511 | 0 | 10,511 | 11,476 |
| April | 9,980 | 0 | 9,980 | 10,896 |
| May | 10,121 | 0 | 10,120 | 11,050 |
| June | 10,023 | 0 | 10,023 | 10,943 |
| July | 10,153 | 0 | 10,153 | 11,085 |
| August | 10,628 | 0 | 10,628 | 11,603 |
| September | 10,005 | 0 | 10,005 | 10,924 |
| October | 10,108 | 0 | 10,108 | 11,036 |
| November | 9,837 | 0 | 9,837 | 10,740 |
| December | 10,207 | 0 | 10,207 | 11,144 |
| Annual | 120,772 | 0 | 120,772 | 131,859 |

Case study 2: The second case study is considered as MT, WT and BSS with the capacities of 30 kW, 15 kW and 513 Ah. The effects of the above-mentioned generating units in a MG system are analyzed in this case study. The electrical energy production of the MT, WT and grid are 96,866 kWh/yr, 23,864 kWh/yr and 1,501 kWh/yr. This indicates that the aforementioned units contribute 79.2%, 19.5% and 1.23% of the total electricity generation at 0.375 R/kWh cost of energy. The application of the MT, WT and BSS has reduced the values of ACS, cost of energy, energy purchased, net energy purchased and energy charge by 97.3%, 65.6%, 98.8%, 99.9% and 99.8% respectively. The KPIs utilized in this case study have been improved owing to the wind penetration and capacity factor of the site, with the values of 19.8% and 18.2%. In a similar way, the thermal energy produced by a boiler has also reduced by 93.4% owing to reuse of waste energy from a MT with the application of a WHR facility. The results obtained in this case study show that the WT and MT are complements of each other with the application of a WHR facility that plays a substantial role in the optimization of the MG system. The utility monthly summary for case study 2 is presented in Table 4.

Table 4 Utility monthly summary for case study 2

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Energy charge (R) |
|---|---|---|---|---|
| January | 148 | 95.8 | 52.4 | 70.07 |
| February | 122 | 0109 | 12.5 | 28.28 |
| March | 122 | 117 | 5.16 | 21.33 |
| April | 153 | 77.4 | 75.7 | 93.07 |
| May | 123 | 110 | 13.6 | 29.54 |
| June | 108 | 303 | -195 | -172.57 |
| July | 124 | 111 | 13 | 29.06 |
| August | 129 | 75.5 | 53.3 | 68.34 |
| September | 148 | 95.2 | 53.2 | 70.88 |
| October | 107 | 98.7 | 8.08 | 22.07 |
| November | 109 | 163 | -54.2 | -37.27 |
| December | 108 | 103 | 4.64 | 18.91 |
| Annual | 1,501 | 1,458 | 42.2 | 241.67 |

## 6. CONCLUSIONS

This paper has presented an efficient method for the assessment of RETs and MT on the economic proficiency of the cogeneration MG system. The cost model that consists of net energy purchased, annual utility bill savings and ACS is utilized in the research work. The model proposed in this study with economic analysis is useful for the independent power providers to supply thermal energy and electricity at minimal operating costs. The outcomes of the research work have validated the influences of the MT, WT and BSS on the reduction of the ATC and improved the performance of the proposed MG system. The strategic method applied in this paper can be utilized to take care of numerous financial issues that are identified with the operation of a power system.

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