Bio-gas Mixed Fuel Micro Gas Turbine Co-Generation for Meeting Power Demand in Australian Remote Areas

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Abstract

Generally, the electricity is purchased from the distribution utility company, however, remote inhabitants can complement their power demand through own generation (using small generator, renewable energy system, etc.) in order to achieve remarkable benefits by lessening electricity bill, availability of supply and using waste and renewable energy resources. Among the alternatives of own power generation, the micro turbine generation is rapidly expanding which has drawn increasing attention due to numerous techno-economic and environmental benefits. This paper examines the feasibility of typical Australian household scale energy generation through turbine generators operating on local bio energy sources. This paper specifically examines the use of simple Anaerobic Digesters for the generation of Bio-gas for running a small turbine generator and their feasibility in the rural household use.

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Key words: Microturbine, Biogas, Co-generation, CHP, Thermal efficiency

1. Introduction

The power generation and distribution within the franchise area became a challenge for the citizen who lived in the countryside. Australian Energy Regulator is promising to take a closer look at the costs of those poles and wires of the regional businesses, irrigation are among the hardest hit [1]. The main issues are set by Australian Energy Regulator (AER) for extra charging on distribution poles and wires. The cost relevant to electricity are three categories such as (i) retail operation costs, such as meter reading, billing, marketing etc. (around 10% of total cost) (ii) network costs (around 45%) and (iii) wholesale electricity costs (45%). The distribution and transmission lines are constructed in the remote areas for resolving the citizen’s conflict of interest. Whereas payback period is a vulnerable issue and treated as subsidized program. In Australian power network, the peak demand is increasing around 2% yearly [2]. Off grid remote area power supply became a priority program for Australia and implementing alternative power source for meeting up the remote areas demand. Among other renewable energy sources, small scale power generation are adopted in Australia, such as (i) Solar Photo Voltaic Cell roof top system, (ii) Small wind turbines, (iii) Gas Fired Co-generation/Tri-generation, (iv) Bio-gas, (v) Internal Combustion (IC)
engine drive generator etc. These off grid generation are established close proximate to consumer and available renewable energy resources as well as back up fuel supply. The choosing of the reliable system mainly depends on overhead cost and technological capabilities. The small scale generators driven by micro gas turbines provide an innovative solution, where mixed fuel/waste gas energy can be used. The accelerating trend towards local micro generation has been recognized with significant performance advantages over diesel/petrol generator. In this paper the energy source is biogas produced in a household fermenter known as an Anaerobic Digestor. The bio-gas is generally a mixture of methane CH₄ (60-70%), carbon dioxide CO₂ (30-40%) and less than 1% of hydrogen sulphide H₂S [3]. An existing micro turbine system can be used for generating electricity. For improving the system performance, the renewable energy sources can also be coupled through combination of anaerobic digesters and solar collectors.

2. Micro turbine technology

A gas turbine is a rotating engine that can produce energy through combustion gases injected over the turbine blades. Energy is added to the gas stream in the combustor, where air is mixed with fuel and ignited. Combustion increases the temperature, velocity, and volume of the gas flow. This is directed through a nozzle over the turbine’s blades, spinning the turbine and powering the compressor. Energy is extracted in the form of shaft power, compressed air, and thrust. Micro turbines are small size unit, now widely available in the 10-50 MW scale. Section view of a typical CHP (combined heat and power) micro turbine unit is presented in the Figure 1[4-5].

Micro turbines are expected to be slightly more efficient than IC engines at comparable scales with waste heat is reused. Wide range of fuel source like natural gas, diesel fuel, kerosene, propane, and biogas can be used in micro turbines. Meeting up the individual needs, micro-turbine development started in 1990. The major manufacturers of micro turbines in 2001 were: Capstone (30-60 KW), Elliot (100 KW CHP system), Ingersol-Rand (70 and250 kW), Bowman (80 kW) in USA, Nissan (2.6 kW) in Japan, Turbec (100 kW) in Europe. Micro turbine (with outputs of 25 kW to 500 kW) is one of the important components in a micro gas turbine engine.

Most designs use a single shaft onto which the radial compressor, radial turbine and generator are all coupled. The rotating speed of the shaft is ranging from 45,000-100,000 rpm. European Union (EU) conducted a comprehensive study on biomass fuel and predicted about 15 GW of biomass co-generation capacity in only 9 EU countries [6]. Micro turbine operates with different fuels, but mostly with natural gases delivered at pressures of 55-90 psi. On the other hand biogas is a low-pressure gas. After step up pressure with centrifugal/scroll-type compressors, it became an alternative renewable fuel source for driving the microturbine electric generator. The poultry litter and pig/cow manures are suitable for producing the low/medium heating value gas, which can be processed to a synthesis gas for the micro turbine. The composition of the biogas is more complex and usually contains H₂ and CO as main combustible components and considerable amounts of CO₂, CH₄ and N₂.


The process flow diagram of integrated micro turbine unit with renewable energy source is shown in Figure 2. The model consists of (i) Bio-gas digester, filtration and storage facility, (ii) Coupling of back
up fuel as LP gas, (iii) Gas Turbine (2 stage), (iv) Direct Solar power unit (64x300mm², 8 rows of 8 mirrors concentrated solar system) vapour absorption type refrigeration system using for bio-gas plant and additional make up steam generator for power turbine, (v) Back up solar PV cell/small wind turbine generation and storage facilities. The basic operational stages of the unit are the first stage compressor and turbine section to feed the power turbine assembly by using the Bio gas (LP gas as contingency). The exhaust from the low pressure turbine passed through a secondary reheat chamber. This will combine with the availability of steam from the solar collector which will utilize a 2 stage boiler capture and transfer system. The storage batteries can be coupled to Solar PV/existing system for improving reliability and small load condition.

![Turbine process flow model](image)

**Figure 2: Turbine process flow model**

### 4. Methodology

The methodology behind the modelling process of the system was based around the steady state analysis of a typical turbine section under operational circumstances. The current electrical requirements of a standard Australian household can vary drastically depending on the geographic location and environmental conditions faced due to both the natural climate and the physical complexities of the household. For the purposes of this paper, the generation requirements have been based around the requirements of a single house. This is modelled around a basic three bedroom low set wood frame central Queensland household. The dwelling has two occupants and lays on approximately 850 square meters of land with the house itself only taking approximately 85 square meters. The house does have a few luxuries like a swimming pool, large 9mx6m shed, internal fish tanks and air-conditioning, although for the purposes of this paper can be scrutinised as a standard household for the region. The power consumption of the dwelling can jump drastically during the cooler months which can be attributed to the increased use of the pool systems and the air conditioners. The winter months generally see an average of approximately 1200 kWh for quarterly bills compared to approximately 2400 kWh for the summer months. The current Tariff’s for the location at time of the completion of this paper are $0.2673 per kWh for Tariff 11 “residential” and $0.1237 per kWh for Tariff 31 “super economy”. To simplify the
calculations for the concept the following assumption for the power charges has been made; last bill for $716.67 for a total of 2343kWh at a combination of Tariff 11 and 31 and additional service charges. This will be simplified down to $716.67/2343kWh = $0.3057 per kWh. The process flow diagram of the model with their respective states in the system is shown in Figure 3. The major equations that were used for the modelling of the output and characteristics of the turbine are given below.

Figure 3: Turbine process flow model

The compression of the incoming air mix in the compressor;

\[ W_c = C_p (T_2 - T_1), \quad E_c = W_c \times m_{f_a(2)} \]

The increase in the temperature of the compressed air through the recuperator;

\[ n_r = \frac{T_{3S} - T_2}{T_0 - T_2}, \quad T_3 = T_{3S} \left( \frac{P_2(1 - P_{13})}{P_2} \right)^{(y-1)/y} \]

The temperature rise through the combustion chamber

\[ Q_{cc} = m_{fa} n_{cc}(h_4 - h_3), \quad m_{f_{cc}} = \frac{Q_{cc}}{LHV_f} \]

The HP turbine the unit is free of the second shaft due to the free turbine nature;

\[ W_{ipT} = \frac{W_c}{n_{ipT}}, \quad E_{ipT} = W_{ipT} (m_{fa} + m_{f_{cc}}) \]

The gasses now enter another combustion chamber for reheat.

\[ Q_{cc} = m_{fa} n_{cc}(h_6 - h_5), \quad m_{f_{rh}} = \frac{Q_{rh}}{LHV_f} \]

The introduction of a possible steam injection phase,

\[ h_7 = \frac{(h_{st-o} m_{f_{st-o}}) + (h_6 m_{f_6})}{m_{f_{st-o}} + m_{f_6}} \]

The efficiency,

\[ = \frac{W_{ipT}}{LHV_f (m_{f_{cc}} + m_{f_{rh}})}, \quad W_{ipT} = c_p (T_7 - T_0) \]
For the process of the solar concentration modules the following has been used for the generation of the conceptual model;

\[
\text{Assumed Radiation Energy } \Phi = 1.366 \text{ kJ/s (kW)},
\]

Concentrated Intensity \(Q_{st} = \Phi A_{sc} R_e n_{st-b}\),

Assumed Boiler Efficiency \(n_{st-b} = 50\%\),

Assumed Reflection Efficiency \(R_e = 50\%\),

\[
\therefore \text{Concentrated Intensity } Q_{st} = 1.366 \times 7.18 \times 0.75 \times 0.75
\]

\[
= 5.517 \text{ kJ/s},
\]

\[
\therefore \text{aiming of saturation point of water at 4 bar is 143.63 deg C}
\]

\[
\therefore \text{Heat required increasing water to temp } Q = m_{fw} c_p (T_2 - T_1)
\]

\[
m_{st-o} = \frac{Q_{st-i}}{c_p(T_o - T_i)}
\]

The process of the solar boiler for the steam addition cycle is a simple heat transfer equation for a fluid flow situation. This can be seen by the following equation.

\[
q_s = c_p \times dT \times m/t
\]

where, \(q_s = \text{Solar heat transfer rate kW (kJ/s)}, m/t = \text{mass flow rate of the product (kg/s)}, c_p = \text{Specific heat of water (kJ/kg K)}\)

The volume of digester can be given by,

\[
V_d = \frac{m_i c_o}{B_r}
\]

Where \(V_d = \text{Digester volume}, m_i = \text{the mass of substrate feed rate in kg/d}, c_o = \text{The % concentration of organic matter and Br = the organic load in kg/d/m}^3\).

5. Results and discussion

The following assumptions were made for the steady state operation of the turbine assembly. Ambient air temperature 270 C, Air pressure 1 bar, Compressor efficiency 85%, Recuperator efficiency 99%, Combustion chamber efficiency 99%, HP turbine efficiency 80%, Reheat chamber efficiency 99%, Recuperator exhaust restriction 99%, steam addition 0 kg/s. Figure 4 shows the increase in the Thermal Efficiencies due to the recuperator being set at an efficiency ratio of 80% [8]. It is important to notice that the increase in the efficiency in the lower pressure ratios compared to the higher ratios. This is a direct result of the lower discharge temperatures in the lower pressure ratios and the inability of the system to recover the heat at the higher pressure ratios due to the increase in the discharge temperature of the compressor. The heat recovery from the generation can be used to heat the water up to 110\120 0C. Addition of the steam increases the mass flow of the airflow in the system. Depending on the entry point the temperature rise or drop will occur. This is reliant on the entry temperature of the steam mix.

For the calculation, the module of solar system has been used with an output of 143 0C. Figure 5 shows the general relationship of the recuperator efficiency and the corresponding thermal efficiency gain in the system with the desired 1500 K and 5 bar are set from the initial findings of the concept model. This is showing the nonlinear increase of the efficiency with the increase in the work of the recuperator and as such the advantage of the work input from the recuperator. Figure 6 shows the theoretical gain of the steam addition cycle for the chosen parameters. This is showing the increase in the thermal efficiency as a function of mass flow rate of steam addition.

The important note here is that the common rule for the steam injection is to limit the addition to approximately 5% when added following the compressor and before the combustion chambers, for reducing the NOx released by the combustion process. In this instance the proposal is for the addition prior to the power turbine to raise the mass flow of the fluid working on the turbine unit. If high levels
greater than the 5% range are to be used investigation would be required to review the affect that the system would have on the downstream recuperator, for the basis of the research it is envisaged that any addition beyond 5% range would require a dedicated second stage turbine for the steam cycle. The solar collector area required for the relative mass flow % for different types of turbine is shown in Figure 7.

Figure 4: Analytical presentation of the system (a) Standard cycle efficiency, (b) Cycle with recuperation of heat

Figure 5: Thermal efficiency vs recuperator efficiency

Figure 6: Thermal efficiency vs steam addition%

Government subsidized program and stimulation program are initiated for encouraging mass people for using CHP (combined heat and power) system for achieving low cost uninterrupted energy. The payback period mainly depends on bio-gas feedstock. The smaller units like the GT1241 will be best suited for personnel offsets of the power costs. The only feasible option for the installation of the typical solar arrangement would be for the installation of a unit well above the required household arrangement of the dwelling, this
will allow for enough credits to be sourced to counter the capital spend of the installation. The digester assembly and the solar collector running the unit at 4 hours a day simply will not be deemed feasible within the modelled range of 700 weeks. Like solar, the generation of the unit needs to be increased to capture the gap between the costs of the electricity and that current tariff arrangement. Payback periods of approximately 340 weeks are possible with this installation.

6. Conclusions

Small-scale micro turbine generation using bio-gas in remote rural regions can replace diesel generators. This is not feasible for the standard house hold but suitable for the agricultural user. A rural property of even small hobby farm may produce the required feed stocks. Enough gas to be supplied for generating required power for typical household requirements, the feed source from minimum 4-5 cows would be required. Micro turbines will be the next generation for small scale power provision in remote areas, especially once their reduced service requirements become apparent. Integration of hot water heat recovery, absorption chilling and backup power functions makes for simple solutions that save money and increase power reliability. This would require additional capital investment on the battery systems and further maintenance but the effective efficiency gains would be feasible using all of the energy sources. This will reduce the huge capital expenditure for power network in the low population area for minimizing the peak loads as well as adding social benefits like clean emissions, reduced greenhouse gas production, and more efficient use of limited natural resources. From the discussion, microturbine bio-gas generation is found as a potential power generation sector in respect to cost-benefit. The reduction of initial expenses of the plant would be competitive compared to the conventional solar and wind power.

References


Mohammad Rasul has obtained his PhD in the area of Energy, Environment and Thermodynamics from University of Queensland, Australia. Currently, he is working as an Associate Professor at Central Queensland University, Australia. He has published over 350 research articles including books and book chapters, and three awarded papers. So far, he has supervised a total of 16 research higher degree students (PhDs and Masters) to completions.