

Energy Saving and GHG Emission Reduction Potentials of Biogas Applications from Wastes for Trigeneration in Hong Kong

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Abstract

To more efficiently utilize the biogas from wastes, a trigeneration scheme has been proposed as a new way of biogas utilization, i.e. generating electric power while hot water and cold water are produced at the same time for hot water supply to the digesters and cooling supply for air-conditioning in nearby buildings. The energy saving and greenhouse gas emission reduction potentials of the biogas trigeneration in Hong Kong were investigated. This scheme could reduce primary energy consumption by 1.2 percent and greenhouse gas emission by 5.7 percent in Hong Kong if all the collected biogas from waste treatment was used for trigeneration. Investigation results show that the biogas trigeneration is an effective method for utilizing the biogas produced from waste treatment.

Keywords: Biogas; Waste treatment; Trigeneration; Greenhouse gas; Energy saving

1. Introduction

Every year, billions of tonnes of solid waste and wastewater are generated in the world. The large amount of wastes pose serious environmental and economical issues concerning with management and disposal of these solid or liquid wastes. One of the environmental problems

directly related to waste treatment is the emission of biogas resulted from the anaerobic decomposition of the biodegradable organic materials contained in solid wastes or wastewater. Biogas is a flammable and potentially harmful gaseous mixture consisting mostly of methane (CH_4) and carbon dioxide (CO_2). When the concentration of methane in air is 5-15 per cent, it will form explosive mixtures, which may pose a public safety issue. Besides, the role of biogas emitted from wastes in global climate change has been increasingly focused recent years. Post-consumer waste is a small contributor to global greenhouse gas (GHG) emissions with total emissions of approximately 1300 Mt CO_2 -eq in 2005. The largest source is landfill methane, followed by wastewater CH_4 and nitrous oxide (N_2O) ^[1].

According to the report of the Intergovernmental Panel on Climate Change (IPPC), the global average surface temperature has increased over the 20th century by about 0.6°C ^[2]. The increasing concentrations of greenhouse gas in atmosphere tend to warm the surface of the earth. The concentrations of atmospheric GHG have continued to increase as a result of human activities. The atmospheric concentration of CO_2 has increased by 31% since 1750. The atmospheric concentration of methane has increased by 151% since 1750 and continues to increase ^[2]. Slightly more than half of the current CH_4 emissions are anthropogenic and about 5 to 20 percent of total global anthropogenic CH_4 emissions is from waste landfills and 8 to 11 percent of that is from wastewater handling ^[3]. So, reducing the GHG emission from wastes contributes to stabilizing GHG concentrations in the atmosphere at a level that would prevent the dangerous anthropogenic interference with the climate system.

On the other hand, biogas from wastes can also be used as fuel for power or thermal energy generation because of its rather high energy content. The content of methane in biogas from waste is usually 50%~60%, and thus the energy content of biogas is 17~20MJ/m³ (the energy content of pure methane is 33.8MJ/m³). Biogas from wastes can also be regard as a kind of renewable energy resource since wastes are produced continuously. If this renewable energy resource is effectively recovered for industrial, commercial, or domestic purpose, i.e. so-called waste-to-energy, large amount of conventional energy resource can be saved and further reduction of GHG emissions can be achieved.

Hong Kong is a regional commerce center with an area of only 1097 square kilometer and a population of seven million. Every year, more than 6 million tonnes of municipal solid waste and 2.6 million cubic meters of sewage are generated in Hong Kong. A large amount of biogas is generated in waste treatment. A part of the biogas generated in Hong Kong is used for power generation and the remainder is flaring. However, the energy utilization efficiency of biogas for power generation is not high, which is usually 30%~40%. It means that about half or even two thirds of biogas energy is wasted without being reused in the process of electricity generation. In order to make biogas utilization more economically and ecologically feasible, more efficient energy production and utilization technologies should be adopted.

To more efficiently utilize biogas from waste, a trigeneration scheme is proposed as a new way for biogas utilization in this paper, i.e. to generate electric power while cold water and hot water are produced at same time for heating and cooling purposes. The main objective of this paper is to introduce the biogas trigeneration technology and to investigate the energy saving and greenhouse gas emission reduction potentials of biogas for trigeneration in Hong Kong.

2. Biogas from Wastes in Hong Kong

2.1 Municipal solid waste and biogas from landfills

Every year, there is enormous municipal solid waste (MSW) generated in Hong Kong, which mainly includes domestic solid waste, commercial solid waste, and industrial solid waste excluding construction and demolition waste, chemical waste and other special wastes. In 2006 alone, there were totally 6.2 million tones MSW generated, of which 45% was reused, recovered, or recycled and the rest went to landfills. Figure 1 shows the quantity of the MSW disposed and recovered in 1991-2006 in Hong Kong, which indicates that the MSW annually disposed in landfills is growing due the increasing total quantity of MSW annually generated although the annual MSW recovered also increases [4]. A growing MSW is posing enormous pressure on landfills.

There are a total of sixteen landfills in Hong Kong, thirteen of which are closed landfill. The remaining three are usually called as Strategic Landfills, which are currently in operation and meet the requirement to dispose the waste generated daily in Hong Kong. Figure 2 shows the location of various landfills in Hong Kong and Table 5 gives the

main features of the closed and existing landfills [5]. Due to an increasing quantity of wastes, the Hong Kong SAR Government has implemented a waste disposal plan [6]. According to this plan, the three new, cost-effective, and more environmentally friendly strategic landfills had been built and were commissioned in 1993, 1994 and 1995, respectively. The three new landfills are isolated from the principal sources of waste arising, so a new network of refuse transfer station had also been developed. The refuse transfer stations coupled with the new landfills compose a comparatively cheap and undoubtedly more environmentally

acceptable disposal option than those used before.

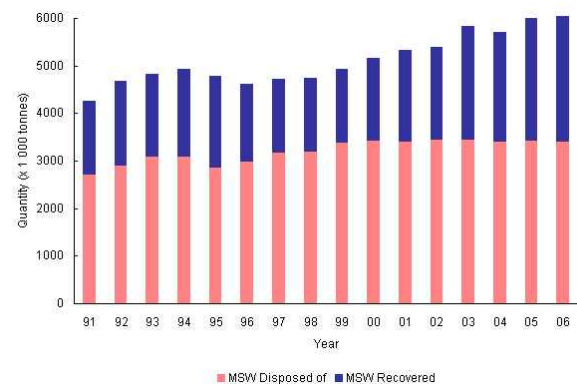


Fig. 1 The MSW disposed and recovered in 1991-2006

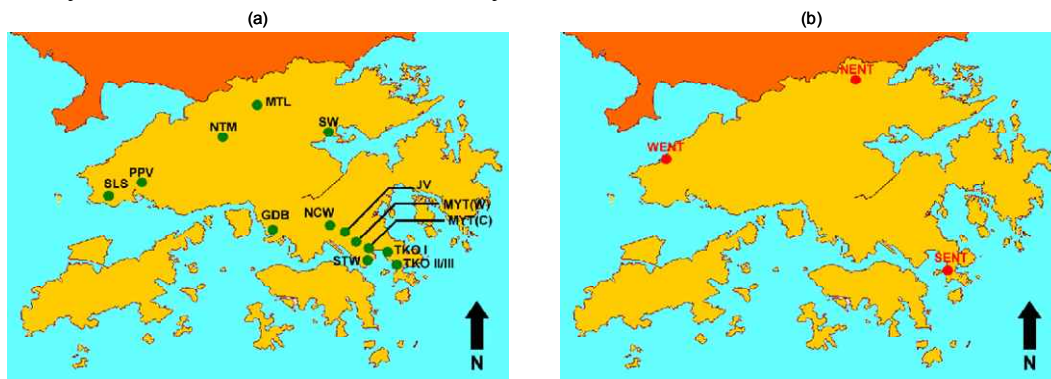


Fig. 2 Locations of the landfills in Hong Kong
(a) Closed landfills; (b) Strategic landfills

Table 1 Information of the landfills in Hong Kong

Name of landfill	Area (ha)	Total waste received (Mt)	Status	Biogas collection rate (m ³ /h)
Jordan Valley (JV)	11	1.5	closed	170
Ma Yau Tong Central (MYT(C))	11	1.0	closed	50 ^a
Ma Yau Tong West (MYT(W))	6	0.6	closed	30 ^a
Sai Tso Wan (STW)	9	1.6	closed	80 ^a
Ngau Chi Wan (NCW)	8	0.7	closed	36 ^a
Siu Lang Shui (SLS)	12	1.2	closed	60 ^a
Ma Tso Lung (MTL)	2	0.2	closed	10 ^a
Ngau Tam Mei (NTM)	2	0.15	closed	8 ^a
Gin Drinkers Bay (GDB)	29	3.5	closed	170
Tseung Kwan O Stage I (TKO I)	68	15.2	closed	596
Tseung Kwan O Stage II/III (TKO II/III)	42	12.6	closed	1770
Shuen Wan (SW)	50	15	closed	410
Pillar Point Valley (PPV)	38	13	closed	850
North East New Territories Landfill (NEWT)	61	about 2200 ^b	existing	4000~5500
South East New Territories Landfill (SENT)	100	about 5340 ^b	existing	5800
West New Territories Landfill (WENT)	110	about 6580 ^b	existing	11000~12000
total				25040~27540

Note: ^a the data is estimated according to the measured result of GDB landfill

^b the current waste intake rate of existing landfills in tonne/day

Table 1 shows the amount of biogas collected from the landfills in Hong Kong in 2006 ^[5]. Most of the data was measured, but the data for some closed landfills was estimated according to the measurement results from similar landfills. The flow rate of biogas collected is about $2.50 \times 10^4 \sim 2.75 \times 10^4 \text{ m}^3/\text{h}$ or $2.194 \times 10^8 \sim 2.413 \times 10^8 \text{ m}^3$ of biogas or $1.036 \times 10^9 \sim 1.139 \times 10^9 \text{ kWh}$ of biomass energy in a year (the heating value of biogas from landfill is about 17000 kJ/m^3). A mean flow rate of $2.63 \times 10^4 \text{ m}^3/\text{h}$ is used in the analysis of this paper.

2.2 Sewage treatment and biogas from sewage treatment works

In Hong Kong, about 2.65 million cubic metres of sewage is produced every day, 30% of which is preliminarily treated, 53% is chemically-enhanced treated and 17% receives secondary treatment. Around 269 sewage treatment facilities including 70 sewage treatment

plants and 199 sewage pumping stations combined with a sewerage network of over 1,525 kilometres in total length are used to collect and treat sewage from residential, commercial and industrial premises in the territory [7].

There are eight major sewage treatment works in Hong Kong. Table 2 shows the main information of the eight major sewage treatment works. Four of them are secondary treatment (ST) works and the others are chemically- enhanced primary treatment (CEPT) works. In the secondary treatment works, the sewage is purified by means of a biological treatment process after the primary treatment has been completed. The organic matter in the settled sewage is decomposed by micro-organisms and a large amount of primary sludge and activated sludge are produced in the biological treatment process. Before the organic matter is transported to landfill, the sludge is stabilized by an anaerobic digestion process. The mixture of the thickened primary and activated sludge is pumped into digestion tanks, which is fully enclosed and insulated to maintain the sludge at 35 in anaerobic conditions, where volatile organic matter in the raw sludge is broken down by biochemical reaction to produce a stable and inoffensive sludge. The digested sludge is then transported to landfills for disposal after being further thickened, conditioned with chemicals, and dewatered. In the digestion process, some biodegradable organic materials contained in the sludge are decomposed under the anaerobic condition and biogas is generated. In a chemically-enhanced primary treatment work, chemicals are added during the treatment to enhance the removal process of suspended solids and biochemical oxygen is needed so that no biogas is produced without the anaerobic sludge digestion process.

From Table 2, the total flow rate of biogas generated from the four major secondary treatment works is 21550m³per day, or 7.9×10⁶m³of biogas or 4.4×10⁷kWh of biomass energy in a year (the heating value of biogas from sewage treatment work is about 20000kJ/m³).

Table 2 List of the major sewage treatment works in Hong Kong

Name of STW	Type of STW	Design daily flow rate of sewage (×10 ³ m ³ /day)	Biogas generation rate (m ³ /day)
Siu Ho Wan STW	CEPT	180	0
Stonecutters Island STW	CEPT	1725	0
Sai Kung STW	CEPT	8	0
Stanley STW	CEPT	11.6	0
Yuen Long STW	ST	70	250
Shek Wu Hui STW	ST	80	4300
Shatin STW	ST	236	11000
Tai Po STW	ST	88	6000
total		2398.6	21550

Therefore, the total available biogas from wastes in Hong Kong is about 2.273×10⁸~2.492×10⁸m³ or 1.080×10⁹~1.183×10⁹kWh every year.

3. Trigeneration using biogas

More than half of the energy end-use in Hong Kong was consumed by residential and commercial buildings, where most of the energy is used for lighting, air-conditioning and hot water supply. Figures 3 and 4 ^[8], respectively, demonstrate the residential and commercial energy end-uses in Hong Kong in 2004. About 69% of the residential energy use and 43% of the commercial energy use are for lighting, air-conditioning, hot water supply and refrigeration purposes. Therefore, a trigeneration to combine cooling, heating, and power generation is good choice for Hong Kong.

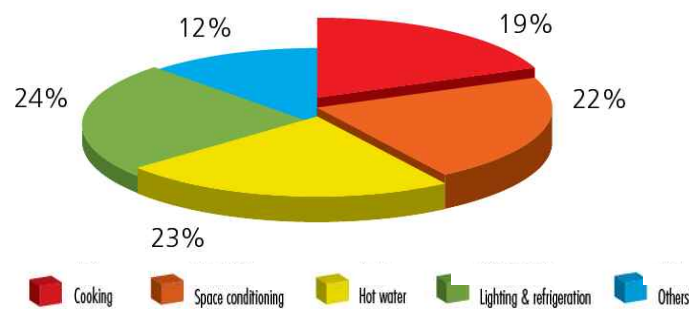


Fig.3 Residential energy end-use in Hong Kong in 2004

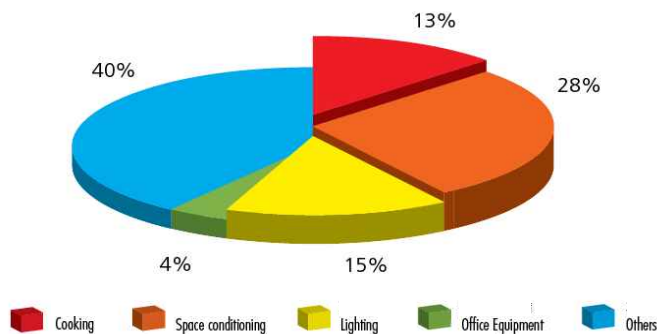


Fig.4 Commercial energy end-use in Hong Kong in 2004

Figure 5 shows the schematic of the trigeneration scheme using biogas as fuel. After dust, sulphur, moisture and so on are removed by a preprocessing system, biogas from landfills (LF) or sewage treatment works is fed into the prime mover. The prime mover drives the power generator to generate electricity through biogas consumption. The power can be used in the works.

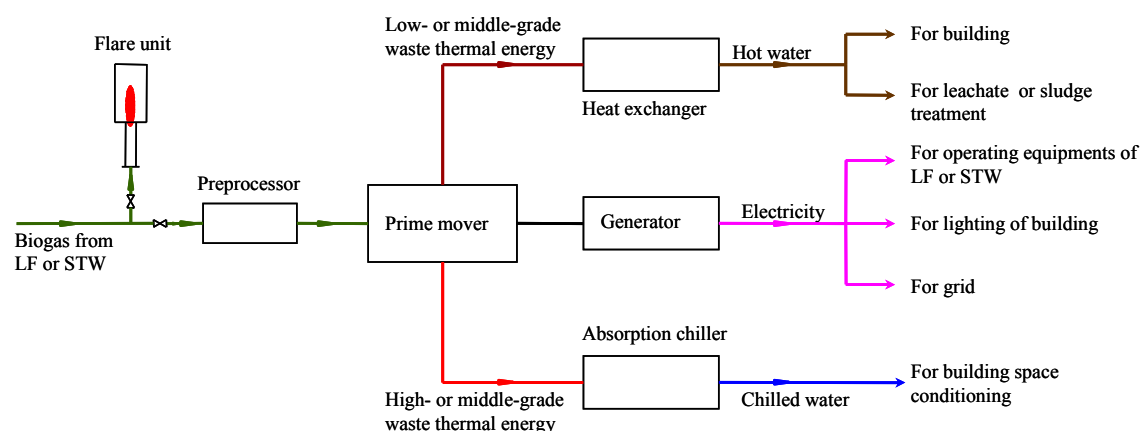


Fig.5 Schematic of biogas trigeneration

While power is generated, the prime mover simultaneously produces thermal energies at different grades. In a conventional power plant, these thermal energies are dissipated into ambient air or water directly or indirectly through heat exchangers. However, some of these waste thermal energies generated in the process of electricity generation can be recovered for further uses. The low- or medium- grade thermal energy from the prime mover can be recovered via a heat exchanger to supply domestic hot water for buildings or for heating sludge or leachate. The high temperature hot water from the prime mover can be used in a desiccant dehumidification system, which is very suitable for a hot and humid climate like Hong Kong.

The high or medium grade thermal energy from the prime mover can be used as the heat source of a thermally activated chiller. An absorption chiller driven by the exhaust gas of a heat engine for refrigeration or for supplying chilled water for air-conditioning has been investigated and reported by many researchers [9-12]. As CFCs-free and HCFCs-free refrigerants can be used, an absorption chiller reduces the risk of ozone depletion and thus is a more environmentally friendly technology. Both a single-effect and a double-effect absorption chiller can be used for cogeneration purpose. A double-effect LiBr/water absorption chiller usually requires a minimum operating temperature of approximately 180°C with a COP of about 1.2, while a single-effect LiBr/water absorption chiller requires a minimum operating temperature of approximately 80°C with a COP of about 0.7. The chilled water generated by an absorption chiller can be used for air-conditioning in an office building of the landfill or sewage treatment work. The surplus chilled water can also be transported to the buildings near the landfill or sewage treatment work through pipe network. Due to the multiple functions, the overall energy efficiency of a biogas trigeneration plant is far higher than that of a conventional power plant.

4. Energy saving and GHG emission reduction potentials

Many types of prime mover can be used for biogas trigeneration, such as reciprocating internal combustion (RIC) engine, gas turbine (GT), steam turbine (ST), stirling engine and fuel cells, etc. Because an RIC engine represents the currently most employed prime mover for biogas utilization, it is chosen here as an example of the biogas trigeneration scheme for analyzing the energy saving and GHG emission reduction potentials in this paper. To evaluate

the energy saving and greenhouse gas emission reduction potentials of biogas trigeneration in Hong Kong, the following three cases are investigated and compared:

Case 1: LFG is directly released into atmosphere

Case 2: LFG are collected and flaring

Case 3: all the collected LFG is fed into a RIC engine-based trigeneration system for generating electricity, chilled water and hot water.

In the analysis, the energy consumption of the biogas collection system is neglected. It is also assumed that the methane content in the biogas is completely combusted.

4.1 Primary energy saving

In order to distinguish different qualities of various energy forms, all the energy saving is computed based on primary energy consumption. The annual primary energy saving (PES) from the trigeneration system can be expressed by:

$$PES = [\frac{E}{\eta_{EG}} + sign \cdot (\frac{Q_C}{COP_{EC} \cdot \eta_{EG}} + \frac{Q_H}{\eta_{HW}})] / 3600 \quad (1)$$

where E , Q_C and Q_H are, respectively, the annual net electrical, cooling, and heating energy outputs from the biogas utilization system; η_{EG} is the power generation efficiency of a conventional power plants; COP_{EC} is the coefficient of performance of an electrically-driven air conditioner or chiller; η_{HW} is the average hot water generation efficiency; $sign$ denotes the mode of the biogas utilization system defined as follows:

$$sign = \begin{cases} 0 & \text{for other mode} \\ 1 & \text{for trigeneration system} \end{cases} \quad (2)$$

The annual net electricity generation from the system is estimated by subtracting the parasitic load from gross electricity output. The parasitic load is the energy consumed by auxiliary equipment (including energy consumption of the biogas processing system) and is usually 2% of the gross power generation by an RIC engine.

$$E = ER_E \cdot TE \cdot (1 - \gamma) \quad (3)$$

The annual cooling and heating gains can be computed as:

$$Q_C = ER_{ExG} \cdot TE \cdot \eta_{EGHE} \cdot COP_{AC} \quad (4)$$

$$Q_H = ER_{JW} \cdot TE \cdot \eta_{HWHE}$$

(5)

where TE is the total fuel energy input into the RIC engine; ER_E , ER_{ExG} and ER_{JW} are, respectively, the electrical energy ratio, exhaust gas thermal energy ratio and jacket water thermal energy ratio compared with the total energy output; η_{EGHE} and η_{HWHE} are, respectively, the efficiencies of the exhaust gas heat exchanger and the jacket hot water heat exchanger. COP_{AC} is the COP of the absorption chiller.

The annual fuel energy utilized from biogas can be estimated by.

$$TE = 365 \times 24 \times G_C \cdot f_U \cdot LHV$$

(6)

where G_C is the volumetric flow rate of biogas collected in m³/h; LHV is the heat value of biogas; f_U is the utilization coefficient of biogas, which is the ratio of biogas utilized to that collected.

In Hong Kong, the power generation efficiency of a conventional power plant (η_{EG}) is estimated to be 35%. The coefficient of performance (COP_{EC}) of an electrically-driven air conditioner or chiller is usually 4.0. The average hot water generation efficiency (η_{HW}) based on primary energy is about 73% in Hong Kong. The efficiencies of the exhaust gas heat exchanger (η_{EGHE}) and the jacket hot water heat exchanger (η_{HWHE}) are assumed to be 85% and 80%, respectively. In this study, a double-effect LiBr/water absorption chiller is used and a COP (COP_{AC}) of 1.2 is assumed. The ER_E , ER_{ExG} and ER_{JW} of a typical biogas-fueled RIC engine are 37%, 24% and 19%, respectively.

Using equations (1)~(6), the annual primary energy savings of the three cases can be found. Figure 6 shows the comparison of the primary energy savings for the three cases. Since the energy consumption of the collection system is negligible, the primary energy savings of Cases 1 and 2 are both zero. One can find from Figure 6 that the primary energy saving of the biogas trigeneration system (Case 3) is about 1.606×10^9 kWh per year in Hong Kong, which accounts for 1.2 percent of the total primary energy consumption in 2004 (1.3496×10^{11} kWh or 11.4 Mtoe^[13]), a significant amount.

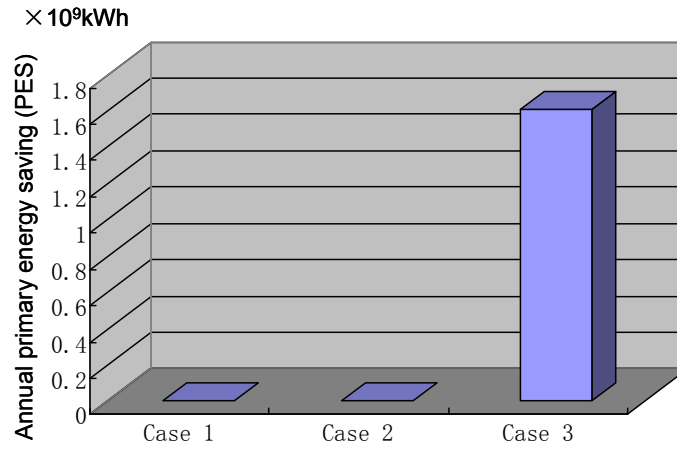


Fig.6 The annual primary energy saving of the three cases

4.2 Greenhouse gas emission reduction

The two main GHGs related to waste treatment are methane and carbon dioxide, which have different global warming potentials. The GWP of methane based on 100 years horizon is 23 while that of carbon dioxide is 1. To assess the greenhouse effect of different gases, a concept of equivalent CO₂ emission is used [2]. The equivalent CO₂ emission can be computed by

$$EQ_{CO_2eq} = 23EQ_{CH_4} + EQ_{CO_2}$$

(7)

where EQ_{CH_4} and EQ_{CO_2} are the emissions of CH₄ and CO₂, respectively. The GHG emission reduction due to the biogas utilization system includes two parts: (1) reduction of equivalent CO₂ emission due to conversion of methane into carbon dioxide in the process of combustion; (2) the avoided CO₂ emission due to primary energy saving. Thus, the GHG emission reduction can be found by:

$$GGER = (EQ_{CO_2eq})_C - (EQ_{CO_2eq})_{T\&U} + (EQ_{CO_2eq})_A \quad (8)$$

where $(EQ_{CO_2eq})_C$ is the annual equivalent CO₂ emission of the collected biogas;

$(EQ_{CO_2eq})_{T\&U}$ is the annual equivalent CO₂ emission quantity of biogas utilization system;

$(EQ_{CO_2eq})_A$ is the annual avoided equivalent CO₂ emission quantity due to primary energy saving; They can be computed by the following equations.

$$(EQ_{CO_2eq})_C = 365 \times 24 G_C (23 \rho_{CH_4} C_{CH_4} + \rho_{CO_2} C_{CO_2}) \quad (9)$$

$$(EQ_{CO_2eq})_{T\&U} = 365 \times 24 G_C \rho_{CO_2} (C_{CH_4} + C_{CO_2}) \quad (10)$$

$$(EQ_{CO_2eq})_A = E \cdot EEF_E + sign \cdot \left(\frac{Q_C}{COP_{EC}} EEF_E + Q_H \cdot EEF_H \right) \quad (11)$$

where C_{CH_4} and C_{CO_2} are, respectively, the concentrations (v/v) of methane and carbon dioxide in biogas; EEF_E and EEF_H are the average effective emission factors of electricity generation and hot water production, which are, respectively, 0.2682g/kJ_e and 0.1239g/kJ_t in Hong Kong.

Using equations (7) to (11), the annual GHG emission reduction of the three cases can be calculated. In the analysis, the methane is assumed to be completely combusted and the greenhouse effect of some trace gases, such as non-methane organic compounds, is neglected. The minor effect of NO_x in exhaust gas of engine is also not considered. The concentrations of methane and carbon dioxide in the biogas from waste landfill are 50% and 45%, and those in the biogas from sewage treatment work are 60% and 35%. The densities of the methane and carbon dioxide are 0.718kg/m³ and 1.98kg/m³. Figure 7 shows the annual GHG emission reduction of the three cases considered in this paper.

Figure 7 shows that flaring the LFG can obviously reduce the GHG emission though its primary energy saving is zero (see Figure 6). The annual GHG reduction through flaring the biogas is 1.742×10⁹kg of CO₂ equivalent, which accounts for about 4.4 percent of the total GHG emission in Hong Kong every year (4.0×10¹⁰kg of CO₂ equivalent^[14]). However, if all the collected biogas is used for trigeneration, the GHG emission reduction will be 2.282×10⁹kg of CO₂ equivalent, which is 5.7 percent of the annual GHG emission in Hong Kong. An increase of 31% in GHG emission reduction can be achieved compared with Case 2. Thus, the reduction is really significant.

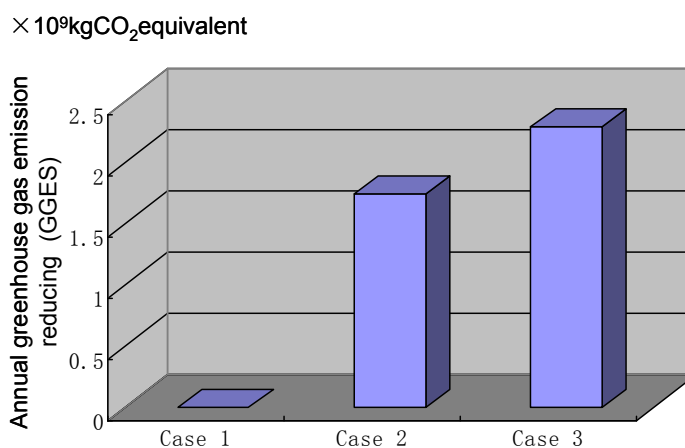


Fig.7 The annual GHG emission reduction of three cases

5. Conclusions

A biogas trigeneration scheme has been introduced in this paper, which uses biogas from wastes as fuel to simultaneously generate electricity, chilled water and hot water. The primary energy saving and greenhouse gas emission reduction potentials of the biogas trigeneration in Hong Kong had been investigated. It will help Hong Kong save about 1.6 billion kWh of primary energy and reduce GHG emission of approximately 2.28 Mt CO₂eq every year. The biogas trigeneration is a good way for waste treatment, which represents the dual beneficial

effects of energy saving from renewable energy source and environmental protection due to greenhouse effect reduction.

References

- [1] Bogner, J., M. Abdelrafie Ahmed, C. Diaz, A. Faaij, Q. Gao, S. Hashimoto, K. Mareckova, R. Pipatti, T. Zhang, Waste Management, In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- [2] IPCC. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2001.
- [3] IPCC. Climate Change 1995. The Science of Climate Change. (J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds)). Published for The Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization/United Nations Environment Programme, Cambridge University Press, UK, 1996.
- [4] Environmental Protection Department of HKSAR. Waste: data & statistics. http://www.epd.gov.hk/epd/english/environmentinhk/waste/data/waste_data.html
- [5] Environmental Protection Department of HKSAR. Waste: problems & solutions. http://www.epd.gov.hk/epd/english/environmentinhk/waste/prob_solutions/msw_racl.html.
- [6] Environmental Protection Department of HKSAR. Waste disposal plan for Hong Kong. 1989.
- [7] Drainage Services Department of HKSAR. Annual report 2005~2006. http://www.dsd.gov.hk/publications_publicity/publicity_materials/annual_reports/index.htm
- [8] The Energy Efficiency Office, Electrical & Mechanical Services Department of HKSAR. Hong Kong Energy End-use Data 2006. <http://www.emsd.gov.hk/emsd/eng/pee/edata.shtml>.
- [9] Maidment GG, Zhao X, Riffat SB and Prosser G. Application of combined heat-and-power and absorption cooling in a supermarket. Applied Energy 1999; 63: 169-190.
- [10] Maidment GG and Prosser G. The use of CHP and absorption cooling in cold storage. Applied Thermal Engineering 2000; 20: 1059-1073.
- [11] Hwang Y. Potential energy benefits of integrated refrigeration system with microturbine and absorption chiller. International Journal of Refrigeration 2004; 27: 816-829.
- [12] Popovic P., Marantan A., Redermacher R. et al.. Integration of microturbine with single-effect exhaust driven absorption chiller and solid wheel desiccant system. ASHRAE Transactions 2002; 108(1): 660-669.

- [13] Department of Industry and Transport Statistics, National Bureau of Statistics, People's Republic of China and Energy Bureau, National Development and Reform Commission, People's Republic of China. China energy statistical yearbook 2006 (in Chinese). China Statistics Press, Beijing, 2007.
- [14] Leung DYC and Lee YT. Greenhouse gas emissions in Hong Kong. *Atmospheric Environment* 2000; 34: 4487-4498.