

The Application of Solid Oxide Fuel Cells in Buildings for Electricity, Heating and Cooling Tri-generation Using Bio-gas from Food Waste

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ABSTRACT

Organic waste has been a major concern in Hong Kong in terms of environmental aspect. Waste-to-Energy system might be an effective solution. By using the bio-gas generated by the Waste-to-Gas system as fuel for SOFC-TG, most of the organic waste could be recycled. The solid oxide fuel cell-based trigeneration energy system (SOFC-TG) is a promising energy solution for green residential buildings. Cooling, heating, and electricity generating can be achieved at a high efficiency with SOFC-absorption cooling trigeneration configuration in the context of Green building and high performance building. The fuel flexibility is a distinguished advantage of SOFC system operating at high temperature, making the bio-gas produced from wastes an attractive alternative to commercial natural gas (e.g. TownGas, Inc) as the fuel for SOFC-TG system in residential building application. This study focuses on the integration of SOFC-TG system with the Distributed Waste Treatment (DWT) system for simultaneous waste treatment and energy recovery. A case study is used for systematic energy analysis to evaluate its feasibility in HK. Series of surveys were arranged to discuss the potential development and constraints for the system.

Keywords: solid oxide fuel cell, tri-generation, waste-to-energy/ waste-derived energy

1. INTRODUCTION

The environmental problem and energy crisis are recognized as the serious global issues after 2015 United Nations Climate Change Conference. Hong Kong, as one of the most densely populated regions, creates 14,300 tons landfilled waste per day (AU, 2015), and consumes 162,356 tera-joules electric power ("Hong Kong Annual Digest of Statistics," 2016). Establishing the building integrated Distributed Waste Treatment (DWT) and Distributed Energy Resource (DER) system offers a promising method for effective waste treatment and energy generation simultaneously.

The organic waste such as food waste contributes to 37% of total landfilled waste but only 6.9% of the food waste was recycled (AU, 2015). Sending the organic waste to the landfill stations not only increases the environmental burdens, but also waste the valuable organic components, as they can be used as useful resources for energy generation or other products. The distributed anaerobic digestion system can treat the organic waste and generate biogas which can be used as a fuel for Solid Oxide Fuel Cell (SOFC) (Chen and Ni, 2014). SOFC is a promising energy conversion device with an efficiency (about 50%) higher than conventional heat engines (typically below 40%). The SOFC-based multi-generation system combining electrochemical power generation and waste-heat recovery can achieve a much higher energy efficiency (i.e. 70 - 95%). The biogas-and SOFC-based tri-generation system with heating, cooling and electricity generation is recognized as one of possible building integrated energy system for its high energy efficiency, low operating cost, quiet operation and low noxious-gas emission.

Although Waste-to-energy (WtE) is an active research area, the building-integrated WtE (BIWTE) system for Distributed Waste Treatment (DWT) and energy generation has rarely been studied to fill this research gap, this study focuses on the integration of SOFC-based trigeneration system with the DWT system for simultaneous waste treatment and energy recovery. The power consumption data of Hotel Icon is used as a case study for systematic energy analysis to evaluate its feasibility in HK. In addition, series of surveys were arranged to discuss the potential development and constraints for the system.

2. WASTE-TO-ENERGY SYSTEM

The proposed BIWTE system consists of a waste-to-gas DWT system and an SOFC-based tri-generation sub-system proposed by Chen et al (Chen & Ni, 2014). The waste-to-clean biogas system consists of the adapted waste-to-biogas system (Curry and Pillay, 2012); and the biogas treatment system (De Arespacochaga et al., 2014), as shown in Figure 1. The two main sources of waste in the system proposed are food waste (FW), from restaurants such as Green or The Market at Hotel ICON, and the hypothetical sludge in anaerobic digestion from an on-site wastewater treatment.

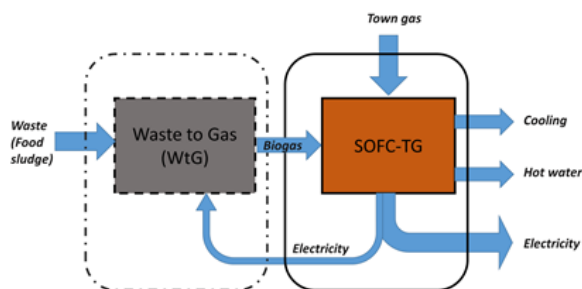


Figure 1: Schematic of the waste to power system based on SOFC-trigeneration

The waste-to-biogas system refers to the anaerobic digestion system for the urban environment by Curry and Pillay (2012). Yet, some modifications were integrated from the original design, such as the excess liquid from the dewatering process is aerated and solely sent to the sewage urban system instead of being recirculated or being used as fertilizer. In addition, the H_2S removal system proposed by the author will be substituted by the system of De Arespacochaga et al. (2015). The biogas treatment system is taken as the original one; including the polishing system configuration based on adsorption technologies by De Arespacochaga et al. (2014).

2.1 Waste-to-Gas (WtG) system

Food waste management has been of great concern for Hong Kong authorities. In 2013, Hong Kong generated 1.36 million tonnes of food waste, of which 1.33 million tonnes (98%) were disposed of at landfills (Audit Commission 2015). Hong Kong is a densely populated city with limited land resources. Thus, alternatives for food waste treatment have been encouraged by Hong Kong Government. The idea of the hypothetical sludge, in anaerobic digestion from an on-site wastewater treatment, is based on existing systems in high performance buildings [e.g. Solaire in the USA (ASHRAE 2008), Business Complex (Kimura and Funamizu, 2012), OHSU Center for Health and Healing (SPU and USMB, 2008), Ikebukuro Sunshine City, and Tokyo Dome (Udagawa 1994) in Japan]. In general, the buildings with on-site wastewater treatment use septic tanks to contain the sludge till a mobile sludge removal vehicle takes it out from the building (Matsuo 2000); or sent back to the city through the sanitary system (ASHRAE 2008). Yet, some buildings in Japan stabilize the sludge in night soil treatment facilities where biosolids are recycled for biogas yield for energy, compost, agriculture, and cement manufacturing (Gaulke, 2007). In this system both types of waste are utilised for anaerobic digestion due to their biogas yield potential.

2.2 Waste-to-Gas (WtG) system

Curry and Pillay (Curry & Pillay, 2012) studied food waste as a sole substrate for anaerobic digestion. The study reviewed the technologies for biogas production from food waste, from which the experimental estimation of 367 m^3 /tonne volatile solids (VS) was recommended by the Environmental Protection Agency (EPA) for mixed food waste biogas generation (65% CH_4 and 35% CO_2). In other study, the biogas generation could reach 1063 m^3 /tonne VS (Prabhu & Mutnuri, 2016). Additionally, the energy value for food waste biogas with 65% methane is considered as 6.25 kWh/m^3 (Curry & Pillay, 2012).

This study proposes the co-digestion of food waste with sewage sludge for biogas generation. Anaerobic co-digestion is a process where two or more substrates with complementary characteristics are mixed for combined

treatment. Prabhu and Mutnuri (Prabhu & Mutnuri, 2016) studied the co-digestion of food waste and sewage sludge. The results of the study showed that for pilot scale digestion a mixing ratio of 1:2 and loading rate of 1g VS/Ld gave the maximum biogas production of 742 ml/gVS Ld with a methane content of 50%, followed by 2 g VS/Ld with biogas yield of 539 ml/gVS Ld. The loading rates are within the range recommended in literature review of 1-5 kgVS/m³ (Curry & Pillay, 2012).

Co-digestion of FW with sludge has several advantages such as higher CH₄ yield at a proper mixing ratio, an accelerated methane production rate, handle two different waste streams, and reduce the costs of food waste management (Prabhu & Mutnuri, 2016; Schiettecatte, Tize, & De Wever, 2014). For example, the FW co-digestion in the pilot project of East Bay Municipal Utility District (EBMUD) in California, USA experienced a three-fold CH₄ yield, better performance from the machines, and costs savings from on-site electrical and thermal generation (Gill-Austern, 2011).

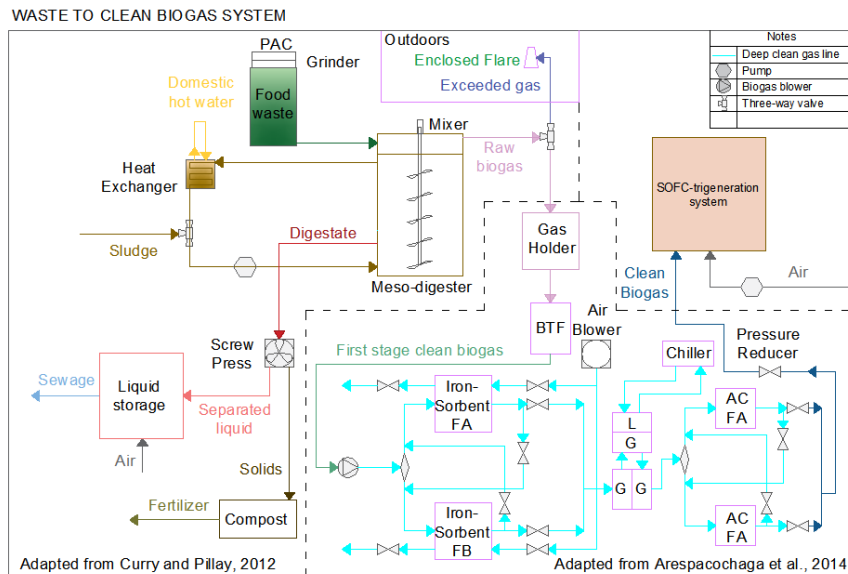


Figure 2: Schematic of the Waste-to-Energy (WtE) system

Researchers (Heo, Jeon, Lee, Kim, & Lee, 2003) studied different food waste and activated sludge co-digestion ratios in a single-stage anaerobic co-digester. The food waste used by the author was simulated Korean food waste which is similar in characteristics with Hong Kong food waste (Zhao & Deng, 2014). The highest methane production rate, with hydraulic retention time (HRT) of 10 days, was present for the ratios of 50:50 and 30:70 with 1.150 and 0.601m³CH₄/m³day, respectively. The organic loading rate varied from 3.14 to 2.60 kgTVS/m³ day. The design of the anaerobic digester in this paper is based on the considerations mentioned above, the daily amount of food waste generated by the hotel is 4300 kg, assuming the food waste mainly comes from 528 consumers (5 kg per person per day) and 1,100 staff (1.5kg per person per day). The required activated sludge for co-digestion ranges from 6.02 Ton/day to 4.3 Ton/day. Ideally the mixing ratio should be kept 50:50, but the food waste supply might fluctuate at the Hotel ICON. Thus, the anaerobic digester is designed with maximum flow allowed, while the methane production rate considers a range of the probable mix ratios possible. The volume of the reactor considers a maximum flow of 8.6 Ton/day and HRT of 10 days. The total working volume with a maximum flow would be 86 m³ ~90 m³. The methane production rate ranges from 98.9 to 51.7 m³CH₄/day. The methane content ranges from 63.3 to 70.4%. Thus, the total biogas production rate varies from 156 to 73.42 m³ biogas/day.

The space required for the installation is based on Tsang et al 's calculations (Tsang, 2013) of a 70 m³ anaerobic digester. The system in this paper is about 22% larger than the system in Tsang's work. Thus, the space required for the anaerobic digester is 44 m², biogas holder is 31 m², food waste tank is 7.5 m², enclosed flare is about 6m², and auxiliary equipment around 10 m². The total space required would be around 100 m² including indoor and outdoor components.

2.3 Biogas treatment system

The biogas produced by the waste-to-biogas system includes several gases that could affect the performance of the SOFC. In particular, H_2S concentration should be reduced to avoid any SOFC deterioration. The biogas treatment system based on Arespacochaga's work (de Arespacochaga et al., 2015), is a previously studied option to clean the biogas and make it more compatible for SOFC. The results showed that after the polishing system the clean CH_4 concentration ranged around 55.1-57.8%. Thus, based on that assumption, the biogas treatment system with the best conditions can provide 108.33 L biogas/min with 62.62 L CH_4 /min, and with the less optimum conditions it can provide 51 L biogas/min with 28.09 L CH_4 /min to the SOFC system. An important consideration for the performance of the SOFC is that the cleaned biogas might include around 7.5-12.5% of N_2 and 1.8-2.9% of O_2 .

2.4 SOFC-TG system

Solid Oxide Fuel Cells (SOFCs) as an efficient energy converter, are superior over other types of fuel cells, in case of biogas feeding operation. Its fuel flexibility benefits from its ability of internal reforming at its high operating temperature (600-800°C), with proper catalysts such as Nickel.

Biogas produced from waste treatment, compose of about 60% CH_4 is a good fuel option for SOFC, with necessary pre-treatment such as desulfuration and drying process. Compared to other biogas exploitation systems such as direct combustion systems (Bruno, Ortega-López, & Coronas, 2009), stationary/mobile internal combustion engines (Basrawi, Yamada, Nakanishi, & Katsumata, 2012; Colmenar-Santos, Zarzuelo-Puch, Borge-Diez, & García-Diéguez, 2016), upgrading system to natural gas grid, SOFC has advantages such as high energy efficiency, low carbon emission, silent operation, etc. These features make the SOFC suitable for distributed cogeneration system for residential applications.

Pilot biogas-powered SOFC plants were installed and demonstrated to be successful. In Chabloz, Switzerland, farm biogas was used to power a 1 kWe SOFC, for more than 5000 hours starting from 2001 (Basrawi et al., 2012). In 2008, Acumentrics (Westwood, USA) launched two 5 kWe biogas-fed SOFCs (BIOSOFC project, LIFE06 ENV/E/000054) in Barcelona and Stockholm ("Laymen's Report,"). Another biogas-powered SOFC pilot plant was installed at Mataró which collected wastewater from different towns and villages in the Maresme region of Barcelona, Spain (de Arespacochaga et al., 2015).

Bloom Energy, the leading SOFC power module supplier, claim that their SOFC system can directly fed with natural gas, or even biogas for 10 years life-span (Devlin, 2013). The electricity efficiency can reach 56 - 60%, while the overall energy efficiency can be improved to over 80% for cogeneration.

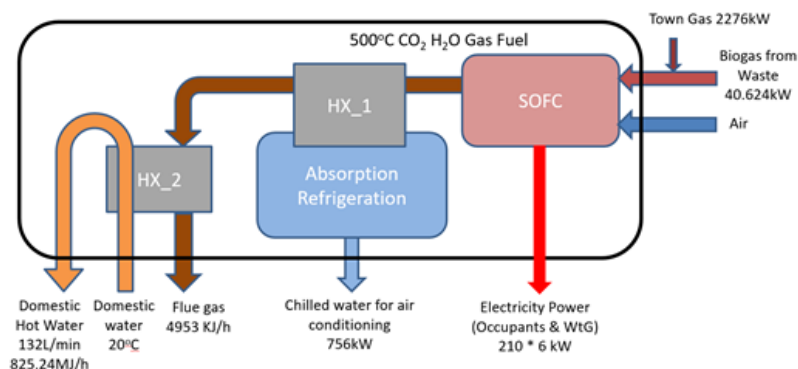


Figure 3: Schematic of the GtE system (SOFC-trigeneration)

In distributed systems, the high temperature waste heat from SOFC can be recovered by refrigeration cycles, turbine, or hot water generators, to achieve a higher system efficiency (even above 90%). Besides, in distributed applications, the need for cooling, hot water and electricity can be partly fulfilled by the tri-generation system at the most time. In this study, a tri-generation system is developed based on 6 units of 210KW SOFC server (ES-5700) from Bloom Energy. The fuel gas to power the SOFCs are the cleaned biogas produced from the Waste to Gas process as introduced in Section 2.1. The configuration of the Gas to Power process are partly adapted from Chen et al's work, as shown in Fig. 3 to briefly described below.

According to the energy utility analysis from HOTEL ICON's management data, a nominal 1210KW electricity power is in demand with a conservative regard to its monthly fluctuation see Figure 4 (ICON, 2016). The SOFCs mainly use the Town gas (a heat value at 17.27MJ/m³) from commercialized pipeworks of Town gas. Inc as the fuel to provide an equivalent 2276KW energy flow into the SOFCs. The composition of Town gas can be referred to Table 1 ("Gas Production of Towngas,").

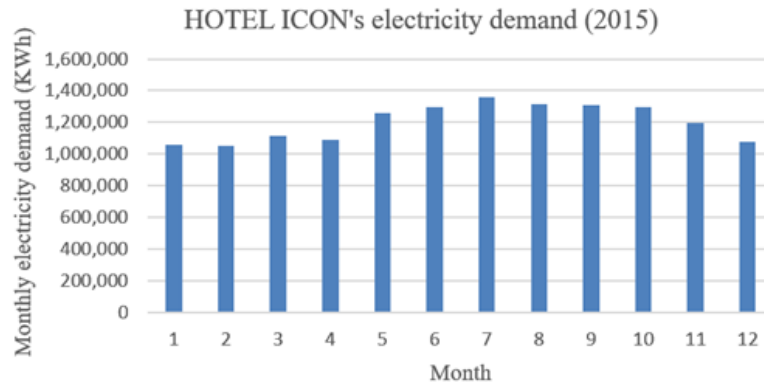


Figure 4: Hotel ICON's electricity demand report, with a monthly average 1210 KWh (ICON, 2016)

Town Gas Characteristics	CO ₂	CH ₄	H ₂	N ₂ +O ₂
Volume fraction	16.3% – 19.9%	1.0% – 3.1%	28.2% – 30.7%	46.3% – 51.8%

Table 1: Town gas characteristics ("Gas Production of Towngas,")

It is important to note that the by-product of waste treatment process: biogas could be another option to power the SOFCs at an optimistically estimated flow rate of 108.33 L/min. The equivalent energy inflow of biogas can be calculated as 40.62 KW. In view of the small amount of biogas production compared to the overall fuel demand by SOFCs, the biogas here only act as an assisting fuel (1.75% of the total fuel heat value), due to the enormous electricity demand by the hotel. The authors hold the view that the waste treatment of residential buildings could be distributed by the combination of WtG and GtE process as demonstrated by this study, though the waste amount cannot fully sustain the hotel power operation, even when the high efficiency SOFC is used. However, in this concept of distributed waste treatment, implicated waste treatment issue are expected to be cut, such as labour cost in waste collection, transportation cost, land source in high density cities where landfill is the prevailing solution to waste treatment, i.e. Hong Kong.

In this study, an absorption refrigeration system (Broad X Non-electric Chiller) manufactured by Broad Group ("Broad Air Conditioning, Borad X Non-electric Chiller (Model Selection & Design Manual),") is chosen to server for the first stage waste heat recovery of the SOFC flue gas. The 500oC flue gas consists of H₂O and CO₂ would exchanging heat with the absorption chiller, leveraged a 756KW cooling capacity in form of chilled water. Consequently, HOTEL ICON's cooling demand can be relieved with 756KW using this absorption chiller. The outflow temperature of flue gas after this first stage heat recovery would be reduced to 160oC. Then the second stage heat recovery will further cools down the temperature to 60oC, generating domestic hot water at a rate of 132L/min.

3. POTENTIAL DEVELOPMENT AND CONSTRAINTS

To investigate the feasibility of combing system in Hong Kong, series surveys are conducted involving experts and potential users. The viewpoints of respondents are noted to discuss technical and legal constraints and the potential market in Hong Kong business environment.

3.1 Technology obstacles and potential market

Some technical defects obstacles limit the actual performance of Waste-to-biogas system combining with the SOFC-TG system. Extra-supports should be provided to control the concentration of sulfide to maintain normal operation and realize satisfactory lifespan of the system. In addition, the fluctuation of power supply and consumption should be considered seriously. Further study is requisite in the simulation tests of combining system.

Moreover, space limitation and unaffordable reinstallation cost extend pay-off period, which might reduce the clients' interest. Majority of respondents prefer projects with short pay-off period (less than five years) due to the lucrative purpose and insufficient supporting funds. On the other hand, the development of DER has raised the importance of waste-to-biogas and new generation fuel cells. Considering the optimistic prospect, majority of respondents have indicated their interests in the application of this system.

3.2 Government supporting and legal constraints

With the advancement of environmental awareness, series of ordinances such as Building Energy Efficiency Ordinance, Building (Energy Efficiency) Regulation, and BEAM-Plus standard were established by Hong Kong government to ensure the rational energy utilization. The Waste Reduction Framework Plan is introduced to encourage the Waste-to-energy. It is agreed that this system could improve energy efficiency and waste recycling performance of buildings and it might obtain financial support funds from the government and social organizations.

Power generation in private sector is cramped by legal restrictions in Hong Kong (Chen and Ni, 2014). Nevertheless, the progressive liberalization of private power generation has achieved a desirable result in mainland China and some European Countries, where established policies to support the BIWTE. Respondents suggested that the operators of this system should obtain the permission from the government in the current legal environment.

4. CONCLUSION

The SOFC-TG and Waste-to-Gas (WtG) system is a possible contribution for remitting environmental and energy crisis. This study is set to investigate the potential development of the combining system from both technical and social concern in hope of searching for available solutions of food waste problem and resource exhaustion. Hotel is selected as the main object of this study for its stable organic waste output and energy demand and the Hotel ICON is analysed as a case study to investigate the application condition in Hong Kong. Based on the current situation, the waste-to-gas system can treat around 4300kg daily organic waste and product 108.33 L/min biogas, the equivalent energy inflow of biogas can be calculated as 40.62 KW. With the fuel of biogas and town gas, the system can realize satisfactory efficiency (50%-80%). However, within the surveys with potential users and technical experts, the overcoming of technical, legal and social constraints of the combining system is indispensable. If the above aspects are addressed, the SOFC-TG with WtG system is promising for building integrated application in Hong Kong and even around the world.

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