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# Distributed Waste Treatment (DWT) in Buildings: Biogas-from-Waste for SOFC-Based Trigeneration

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**Abstract:** Organic waste has been a major concern in terms of environmental aspect. The application of Distributed Waste Treatment (DWT) reduces the environmental influences and improves the integrated utilization rate of recyclable energy and materials within organic waste. Organic waste in buildings can be recycled by the Waste-to-Gas system to generate biogas as fuel for SOFC based Trigeneration (SOFC-TG) system. This combined system is a promising energy solution where cooling, heating and electricity generation are achieved at a high efficiency with SOFC-absorption cooling trigeneration configuration for green buildings. The fuel flexibility of SOFC makes the biogas-from-waste an attractive alternative to commercial energy source (e.g., natural gas) as fuel for the combined systems for building application. This study discusses the application of SOFC-based trigeneration using biogas-from-waste and a case study of Hotel Icon Hong Kong is adopted to evaluate its feasibility.

**Key words:** waste-to-energy, solid oxide fuel cell, tri-generation

## 1. Introduction

The growing energy consumption has already raised global concerns over supply difficulties, "energy crisis" and serious environmental impacts (such as ozone layer depletion and climate change). Especially, the global contribution from buildings towards energy consumption has exceeded other sectors such as transportation and industrial sectors [1]. In 2016, China's total primary energy consumption has reached 4.36 billion tons of standard coal equivalent as a new record [2], where building sector accounts for 15-16% [3]. The current situation in building energy consumption certainly restricts China's development. Since the United Nation Climate Change Conference 2015, more studies have tried to reduce building energy consumption by improving energy efficiency or reducing energy-wasting behaviours. However, there are only a few researches focus on recycling energy from waste to achieve a better building-integrated energy efficiency.

During the building operation process, occupants will produce abundant organic waste, including food waste and sludge. Benešová et al. (2016) noted that organic matter (28%) is the most important component in household waste [4]. In Hong Kong, especially, daily output of food waste is 3,382 tons which accounts for 33% of total municipal waste [5], however, only 6.9% of food waste is effectively recycled [6]. In China, 98% of disposed waste is treated in insufficient methods (landfill or incineration) [7]. Insufficient organic waste treatment is not only a cause of environmental pollution but also a waste of unused chemical energy stored in the waste. Unpleasant smell, long transportation distance, and intricate process are important reasons for low recycling efficiency.

The concept of "Distributed Waste Treatment (DWT)" is therefore proposed based on above

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characteristics. DWT is an approach to deal with different types of wastes with respect to location and characteristics of the source. It has the advantages of a more effective waste collection and recycling. Originally, Zurbrügg (2002) proposed decentralized composting approach aiming to replace the conventional house-to-house waste collection and centralized treatment to enhance waste recycling efficiency and reduce transportation [8]. Righi et al. (2013) indicate that DWT for sewage sludge and food waste has better performance in life cycle assessment and fewer environmental impacts [9]. Considering current situations in Hong Kong, DWT is a potential method to improve recycling efficiency of organic waste and void possible environmental impacts.

In China, biogas generation is a proven technique for organic waste treatment. According to De Clerq et al. (2017) [7], the government planned 242 food waste treatment facilities in China by the end of 2015 and most facilities adopt biogas generation technology. However, serious operational issues (low methane content, high impurity content, and unstable supplement) perplex users of these facilities. These characteristics require a high fuel-flexibility of biogas consumers. A solid oxide fuel cell (SOFC) is an electrochemical conversion device that produces electricity directly from oxidizing a fuel high-efficiently and eco-friendly [10]. A SOFC is characterized by its high fuel-flexibility, high energy efficiency performance, low environmental impacts, and long lifespan. SOFCs can be fuelled by both biogas and natural gas [11, 12]. The energy efficiency of SOFC is 55%-65% [13], and the energy efficiency of SOFC-based multi-generation systems can even achieve 80%-90%, which is much higher than traditional thermal power generation systems [14]. In addition, SOFC-based multi-generations can effectively reduce the emission of greenhouse gases ($CO_2$) and gaseous pollutants (NOx, CO, and $SO_2$) [15]. Therefore, the SOFC-based multi-generation system using biogas from organic waste is a potential application of DWT for green buildings.

## 2. Waste-to-Energy (WtE) System

The organic waste such as food waste contributes to 37% of total landfilled waste but only 6.9% of the food waste was recycled [6]. Landfilled organic waste is not only an environmental burden but also a waste of useful resources for energy generation or other products. Anaerobic digestion is an efficient biogas recycling and treatment technique that transfers energy in organic waste to bio-fuel (biogas). Biogas-from-waste can be adopted as a fuel for the SOFC, which is an electrochemical device with higher energy efficiency (55%-65%) than conventional heat engines (typically below 40%) [14]. The SOFC-based tri-generation system with heating, cooling and electricity generation is one of popular building integrated energy systems 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 application of WtE for building-integrated DWT and energy generation has rarely been studied. To fill this research gap, this study focuses on the integration of building-integrated organic waste treatment and SOFC-based trigeneration system. The power consumption data of Hotel Icon Hong Kong is used as a case study for systematic energy analysis to evaluate its feasibility.

The proposed system (shown as Fig. 2) is made up of Waste-to-Energy system and SOFC Trigeneration system. On one hand, Waste-to-Energy system utilizing anaerobic digestion provides an effective mean of waste treatment. On the other hand, it supports SOFC Trigeneration system with supplementary fuel source. Regarding the trigeneration system, it contains three subsystems, which are SOFC system, adsorption cooling system and water heating system. SOFC fed with clean biogas and town gas can generate electricity together with massive waste heat. These waste heat are recovered through adsorption cooling system and water heating. The adsorption cooling system can provide chilled water for air conditioning while water heating system can provide domestic hot water. In addition, Waste-to-Energy system can be fed with hot water and electricity generated by SOFC Trigeneration system to fulfil its operational demand of temperature and electricity.

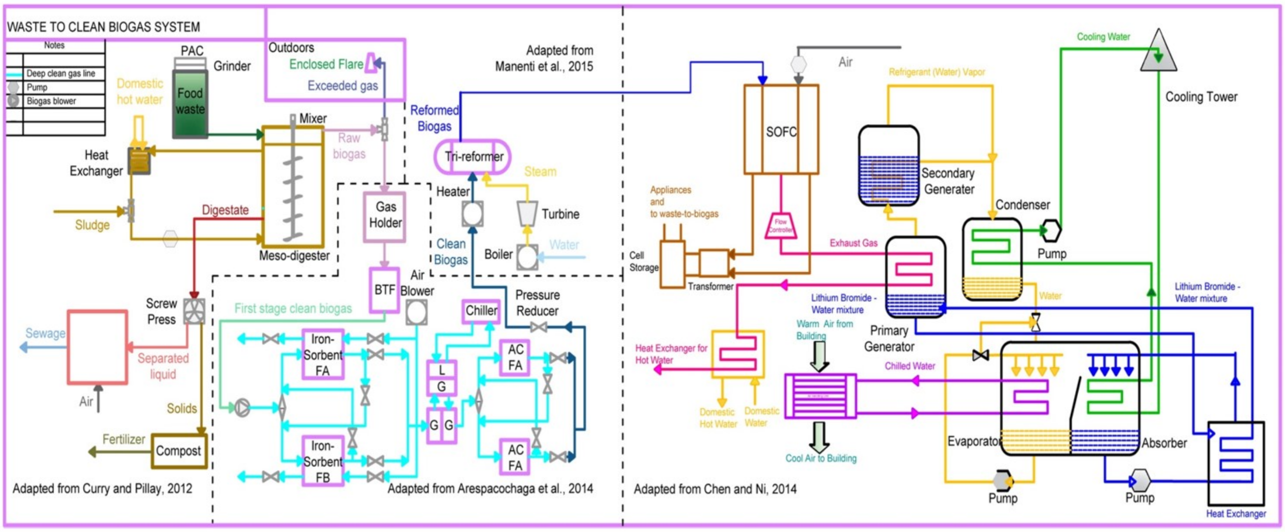


**Fig. 1 Flow chart of the combined system.**

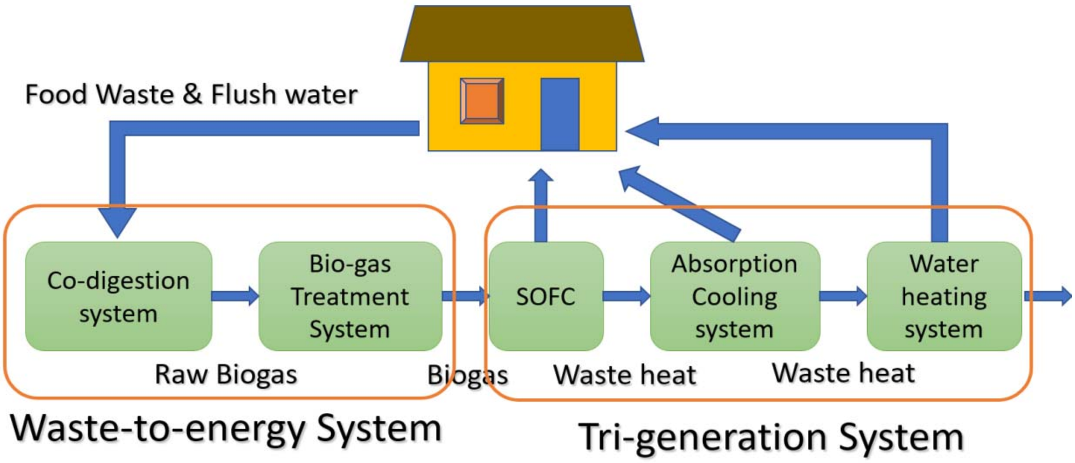


**Fig. 2 Schematic of the SOFC-based trigeneration using Biogas-from-waste.**

*2.1 Waste-to-biogas System*

Previous research has demonstrated the technology for biogas production from waste [7]. This research illustrates a Suzhou kitchen waste treatment project that produce biogas via anaerobic digestion (AD) of animal fodder, biodiesel and effluent wastewater. The food waste from kitchen contains 90% water and a volatile solids-to-total solid (VS/TS) ratio of 85.5. The estimated biogas production can reach 20,000 m3/d from 50 t/d of animal fodder, 20 t/d of biodiesel and 300 t/d of effluent wastewater. Another study utilizes food waste as a sole substrate for AD [16]. The estimated biogas generation can reach 367 $m^3$ per ton volatile solid with 65% methane. Additionally, Prabhu and Mutnuri (2016) illustrate a case of biogas generation of 1063 (mlg−1VS) with 58% of methane [17].

This study proposes an anaerobic digestion of food waste with sludge to generate biogas. Anaerobic digestion refers to a waste treatment process where two or more substrates with complementary characteristics are mixed. It has the advantages of high methane yield (with proper mixing ratio), accelerated generation rate of methane, multiple waste streams handling, and low food waste management cost [17, 18]. For example, the FW co-digestion in the pilot project of East Bay Municipal Utility District (EBMUD) in California, USA experienced a three-fold $CH_4$ yield, better performance from the machines, and costs savings from on-site electrical and thermal generation [19].

Heo, Jeon, Lee, Kim, & Lee (2003) analyze different ratios of food waste to activated sludge co-digestion in a single-stage anaerobic co-digester [20]. The food waste used is simulated Korean food waste which has similar characteristics comparing with China food waste [21]. 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 0.601 $m^3CH4/m^3day$ respectively. The organic loading rate varied from 3.14 to 2.60 $kgTVS/m^3$ day. The design of the anaerobic digester in this paper is based on the considerations mentioned above. Assuming the food waste mainly comes from 528 consumers (5 kg per person per day) and 1,100 staff (1.5 kg per person per day), 4300 kg food waste can be generated every day. The amount of activated sludge required 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 should be designed with maximum flow allowed and the methane production rate should consider 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 86-90 $m^3$. The methane production rate ranges from 98.9 to 51.7 $m^3CH4/day$. The methane content ranges from 63.3 to 70.4%. Thus, the total biogas production rate varies from 156 to 73.42 $m^3$ biogas/day.

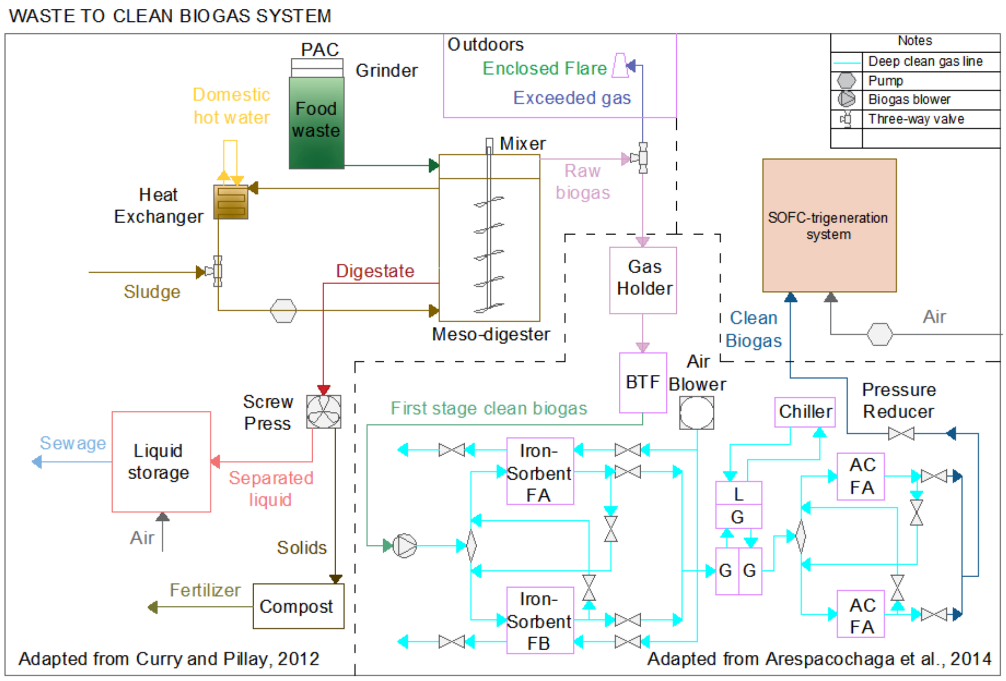


**Fig. 3 Schematic of the Waste-to-Energy (WtE) system.**

*2.2 Biogas Pre-treatment System*

The biogas produced by the waste-to-biogas system includes several impurities ($H_2O$, $H_2S$, and siloxanes) that could affect the performance of SOFCs. Hydrogen sulfide ($H_2S$) requires removal from raw biogas because it may corrode the metallic equipment [22] and especially, $H_2S$ is highly poisonous to the nickel catalyst present in any pre-reformer for SOFCs [23]. In addition, $H_2S$ may be oxidized to form oxides of sulphur (SOx) [$H_2S + (x+1) O^{2-} \rightarrow H_2O+SO_X$], and $SO_X$ may further react with moisture ($H_2O$) to form sulfuric acid ($H_2SO_4$).

$$SO_X+(1.5-0.5x)O_2+H_2O \rightarrow H_2SO_4;$$

$$SO_3 + H_2O \rightarrow H_2SO_4$$

Another main deterrent of SOFCs is siloxane [$H(OSiH_2)nOH$]. Trendewicz and Braun (2013) defined siloxanes as "highly volatile, large organic compounds comprised of silicon, oxygen and alkanes" [22]. Siloxanes may be oxidized to from silicon oxide, especially, silica ($SiO_2$) in high temperature.

$$H(OSiH_2)nOH+nO_2 \rightarrow nSiO_2+(n+1)H_2O$$

The $SiO_2$ glassy deposits on equipment surface may fill the porous structure and obstruct biogas supplement, which is a main cause for frequent maintenance or even SOFC failure [24]. Therefore, a pre-treatment process (shown as Fig. 4) is necessary before using raw biogas for power generation.

2.2.1 Iron-Based Adsorbent Filter

Numerous biological, physical and chemical techniques can be adopted to remove $H_2S$. However, adsorption is the unique approach that fulfils the requirement of fuel cell [24]. Adsorption is a physicochemical process to remove $H_2S$. As the physical adsorption at ambient temperature is ineffective, iron based adsorption should be adopted. The adsorbent of the iron based adsorption filter is iron oxide. When biogas pass through the adsorption section, Iron oxide reacts with hydrogen sulphide and

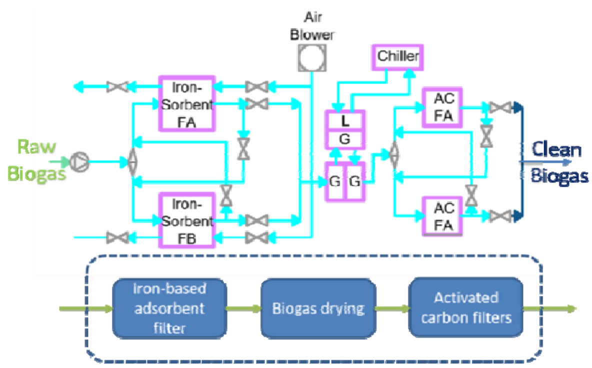


**Fig. 4 Schematic of the Biogas Pre-treatment system.**

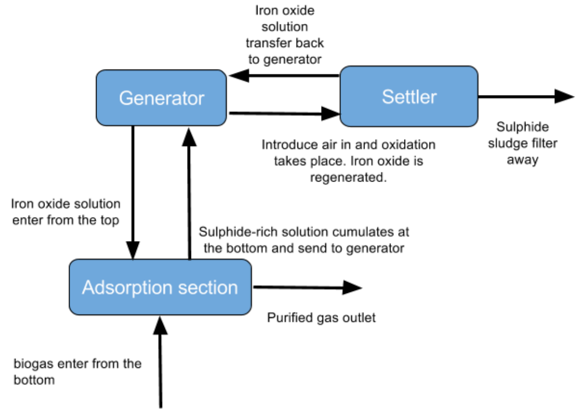


**Fig. 5 Schematic of Iron-based adsorbent filter.**

forms sulphide-rich solution. The purified biogas can then be transferred to the next treatment process.

The Sulphide-rich solution cumulated at the bottom of adsorption section will then be transferred to generator, where Iron oxide is regenerated. Fresh air will be introduced to the generator to enable oxidation. The regenerated iron oxide solution will be pumped back to adsorption section. The Iron sulphide solution remaining in generator will be transferred to the settler, where sulphide sludge can be settled down and filtered away.

### *2.3 Biogas Drying and Activated Carbon Filters*

The refrigeration techniques are carried out for biogas drying process. The power generation system may benefit from biogas drying because this reduces the risk of corrosion caused by residue (H2S). In addition to water vapor, Arespacochaga et al. (2015) note some other impurities such as aromatics and siloxanes can also be partially removed [24]. The refrigeration techniques can remove up to 50% of siloxanes in raw biogas-from-waste [25], however, it cannot achieve the overall siloxane removal requirements for SOFCs and a further treatment is still required after biogas drying process [26].

Activated carbon adsorption is adopted as a post-treatment after biogas drying process. The biogas drying process reduces the siloxane concentration and extend the lifespan of activated carbon absorption filters. The activated carbon adsorption techniques have been widely used for landfilled gas treatment [27-29]. According to Shin et al. (2002) [27], in addition to siloxanes, the activated carbon filters can also effectively adsorb aromatics (such as benzene and toluene), chlorinated compounds (such as chloroform and carbon tetrachloride) and sulfurs (such as residual $H_2S$).

Using operation data of Hotel Icon Hong Kong for calculation, 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 SOFC systems. 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 $O_2$.

## 3. SOFC-based Trigeneration System

As an efficient energy converter, Solid Oxide Fuel Cells (SOFCs) are superior over other types of fuel cells in terms of biogas feeding operation. It has relatively high fuel flexibility due to its ability of internal reforming at its high operating temperature (600-800°C), with proper catalysts such as Nickel. Biogas-from-waste composing about 60% CH4 is an effective fuel option for SOFCs. Moreover, by utilizing the tri-reforming of methane, the efficiency of fuel combustion can be further enhanced [30]. Compared to other biogas exploitation systems such as direct combustion systems [31], stationary/mobile internal combustion engines [32, 33], upgrading system to natural gas grid, SOFC has the advantages of high energy efficiency, low carbon emission, silent operation, etc. Because of these features, SOFC is suitable for distributed multi-generation system for building applications.

Pilot biogas-powered SOFC plants were installed and demonstrated to be successful. In Chabloz, Switzerland, a 1 kWe SOFC consumed farm biogas had been used for more than 5000 hours starting from 2001 [32]. 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 [24]. The leading SOFC power module supplier Bloom Energy, claim that their SOFC system can be directly fed with natural gas, or even biogas for 10-year life-span [34]. The electricity efficiency can reach 56-60%, while the overall energy efficiency for cogeneration can be improved to over 80%.

In distributed systems, the high temperature waste heat from SOFC can be recovered by refrigeration cycles, turbine, or hot water generators, so that a higher system efficiency can be achieved (even above 90%). Besides, in distributed system applications, the demand 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 210 KW 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. 6 to briefly described below.

According to the energy utility analysis from HOTEL ICON's management data, a nominal 1210 KW electricity power is in demand with a conservative regard to its monthly fluctuation see Fig. 7 (ICON, 2016). The SOFCs mainly use the Town gas (a heat value at 17.27 $MJ/m^3$) from commercialized pipeworks of Town gas. Inc as the fuel to provide an equivalent 2276 KW energy flow into the SOFCs. The composition of Town gas can be referred to Table 1 ("Hong Kong Towngas").

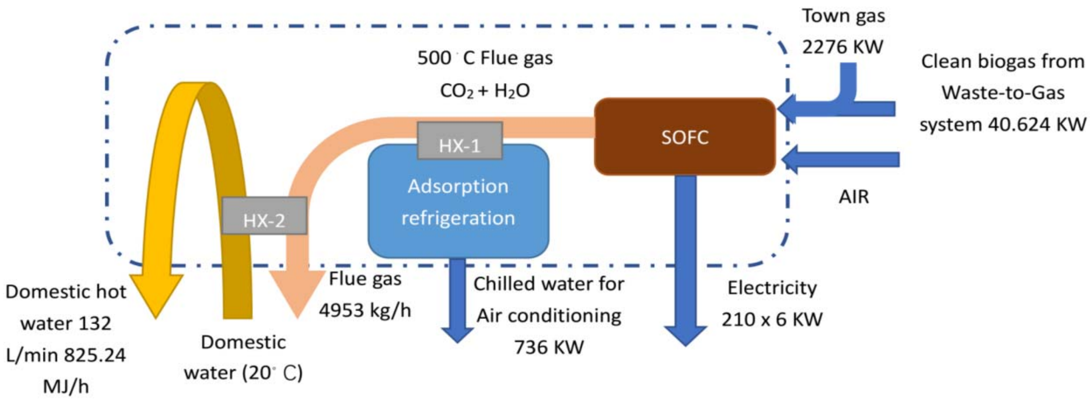


**Fig. 6 Schematic of SOFC-trigeneration system in Hotel Icon.**


**Fig. 7 Hotel ICON's electricity demand report, with a monthly average 1210 KWh.**

**Table 1 Town gas characteristics ("Gas Production of Towngas").**

| 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% |

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 WTE and energy utilization 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 is 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 such as 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 first stage waste heat recovery of the SOFC flue gas. The 500°C flue gas consists of $H_2O$ and $CO_2$ can transfer heat to the absorption chiller through heat exchanger, leveraged a 756 KW cooling capacity in form of chilled water. Consequently, HOTEL ICON's cooling demand can be relieved with 756 KW using this absorption chiller. The outflow temperature of flue gas after this first stage heat recovery would be reduced to 160°C. Then the second stage heat recovery will further cool down the temperature to 60°C, generating domestic hot water at a rate of 132 L/min.

## 4. Potential Development and Constrains

Interviews are conducted involving experts (25% senior government officers; 25% university professionals) and potential users (25% property managers; 25% building occupants) to study the potential development of combined system. Different points of view from respondents are studied to discuss technical and legal constraints and the potential market in Hong Kong business environment.

*4.1 Market and Technique Obstacles*

Several technical obstacles that might limit the actual performance of waste-to-biogas system combining with the SOFC-trigeneration system are being aware. Extra-supports should be provided to control the concentration of sulfide and $SiO_2$ for stable operation and lifespan of the combining system. In addition, the fluctuation of power supply and consumption should be considered seriously. Further study is requisite in the simulation tests of the system.

Moreover, pay-off period is extended due to space limitation and expensive reinstallation cost, which might reduce the clients' interest. Refer to Tsang's calculation method for an anaerobic digester [35], the space requirements for the equipment in this study are simulated. The area for anaerobic digester is 44 $m^2$, biogas holder is 31 $m^2$, food waste tank is 7.5 $m^2$, enclosed flare is about 6 $m^2$, and auxiliary equipment around 10 $m^2$. The total space required would be around 100 $m^2$ including indoor and outdoor components. 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 distributed energy resource has raised the awareness of waste-to-biogas and new generation fuel cells. Considering the optimistic prospect, the majority have indicated their interests in the application of this system.

*4.2 Government Supporting and Legal Constraints*

With the growing 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 can improve energy efficiency and waste recycling performance of buildings and it might obtain financial support funds from the government and social organizations such as CLP Eco Building Fund.

Power generation in private sector is cramped by legal restrictions in Hong Kong [14]. Nevertheless, the progressive liberalization of private power generation has achieved a desirable result in some European Countries (such as German), where established policies to support the building-integrated waste-to-energy systems. Half expert respondents mentioned that the operators of this system should obtain the permission from the government in the current legal environment in Hong Kong.

## 5. Conclusion

The combination of Tri-generation System and Waste-to-Energy (WTE) system has the potential to remit waste treatment problem and growing energy waste in buildings. The purpose of this study is to investigate the potential development of the DWT systems from both technical and social concern in hope of searching promising solutions to tackle urban rubbish problem and resource exhaustion. Considering the organic waste output and energy demand of a building, hotel has been selected as the main object for this investigation and the Hotel ICON is analysed as a case study to evaluate the application condition in Hong Kong. Based on the current situation, the waste-to-gas system can treat around 4300kg daily organic waste and produce 108.33 L/min biogas, the equivalent energy inflow of biogas can be calculated as 40.62 KW. The system is flexible in terms of fuel selection (both biogas and town gas) and can achieve satisfactory efficiency (50%-80%). However, refer to the interviewees, overcoming technical, legal and social constraints of the combined system is indispensable in current conditions. Further studies should be conducted for steady operation of SOFC-based trigeneration using biogas-from-waste for green buildings.

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## References

[1] Y. K. Juan, P. Gao and J. Wang, A hybrid decision support system for sustainable office building renovation and energy performance improvement, *Energy and Buildings* 42 (2010) (3) 290-297.

[2] National Bureau of Statistics of China, *Statistical Communiqué of the People's Republic of China on the 2016 National Economic and Social Development*, Beijing, 2017.

[3] W. Wei and L. Y. He, China building energy consumption: Definitions and measures from an operational perspective, *Energies* 10 (2017) (5) 582.

[4] L. Benešová, A. Závodskáand J. Šmíd, The separation of household organic waste as a method of municipal waste reduction in the Czech Republic, *Journal of Solid Waste Technology & Management* 42 (2016). (1).

[5] Environment Protection Department, *Monitoring of Solid Waste in Hong Kong: Waste Statistics for 2015*, Hong Kong, 2017.

[6] I. E. W. K. Au, *Development of Waste-to-Energy Facilities in Hong Kong*, E. P. Department, Trans., 2015.

[7] D. De Clercq, Z. Wen and F. Fan, Performance evaluation of restaurant food waste and biowaste to biogas pilot projects in China and implications for national policy, *Journal of Environmental Management* 189 (2017) 115-124.

[8] C. Zurbrugg, Urban solid waste management in low-income countries of Asia: How to cope with the garbage crisis, in: *Scientific Committee on Problems of the Environment (SCOPE) Urban Solid Waste Management Review Session*, Durban, South Africa, 2002, pp. 1-13.

[9] S. Righi, L. Oliviero, M. Pedrini, A. Buscaroli and C. Della Casa, Life Cycle Assessment of management systems for sewage sludge and food waste: Centralized and decentralized approaches, *Journal of Cleaner Production* 44 (2013) 8-17.

[10] Z. Dimitrova and F. Maréchal, Environomic design for electric vehicles with an integrated solid oxide fuel cell (SOFC) unit as a range extender, *Renewable Energy* 112 (2017) 124-142.

[11] J. Liu and S. A. Barnett, Operation of anode-supported solid oxide fuel cells on methane and natural gas, *Solid State Ionics* 158 (2003) (1) 11-16.

[12] A. Lanzini, H. Madi, V. Chiodo, D. Papurello, S. Maisano and M. Santarelli, Dealing with fuel contaminants in biogas-fed solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) plants: Degradation of catalytic and electro-catalytic active surfaces and related gas purification methods, *Progress in Energy and Combustion Science* 61 (2017) 150-188.

[13] H. Zhu and R. J. Kee, Thermodynamics of SOFC efficiency and fuel utilization as functions of fuel mixtures and operating conditions, *Journal of Power Sources* 161 (2006) (2) 957-964.

[14] J. M. P. Chen and M. Ni, Economic analysis of a solid oxide fuel cell cogeneration/trigeneration system for hotels in Hong Kong, *Energy and Buildings* 75 (2014) 160-169.

[15] H. I. Onovwiona and V. I. Ugursal, Residential cogeneration systems: Review of the current technology, *Renewable & Sustainable Energy Reviews* 8 (2004) 1-43.

[16] N. Curry and P. Pillay, Biogas prediction and design of a food waste to energy system for the urban environment, *Renewable Energy* 41 (2012) 200-209.

[17] M. S. Prabhu and S. Mutnuri, Anaerobic co-digestion of sewage sludge and food waste, *Waste Management & Research* (2016).

[18] W. Schiettecatte, R. Tize and H. De Wever, Comparison of costs for three hypothetical alternative kitchen waste management systems, *Waste Management & Research* (2014).

[19] D. Gill-Austern, *From Waste to Energy*, 2011.

[20] S. J. Heo, Y. J. Jeon, J. H. Lee, H. T. Kim and K. W. Lee, Antioxidant effect of enzymatic hydrolyzate from a Kelp, *Ecklonia cava. Algae* 18 (2003) (4) 341-347.

[21] Y. Zhao and W. Deng, Environmental impacts of different food waste resource technologies and the effects of energy mix, *Resources, Conservation and Recycling* 92 (2014) 214-221.

[22] A. A. Trendewicz and R. J. Braun,. Techno-economic analysis of solid oxide fuel cell-based combined heat and power systems for biogas utilization at wastewater treatment facilities, *Journal of Power Sources* 233 (2013) 380-393.

[23] C. J. Laycock, J. Staniforth and M. Ormerod, Improving the sulphur tolerance of nickel catalysts for running solid oxide fuel cells on waste biogas, *ECS Transactions* 16 (2009) (50) 177-188.

[24] N. De Arespacochaga, C. Valderrama, J. Raich-Montiu, M. Crest, S. Mehta and J. L. Cortina, Understanding the effects of the origin, occurrence, monitoring, control, fate and removal of siloxanes on the energetic valorization of sewage biogas — A review, *Renewable and Sustainable Energy Reviews* 52 (2015) 366-381.

[25] E. Wheless and J. Pierce, Siloxanes in landfill and digester gas update, in: *Proceedings of the 27th SWANA Landfill Gas Symposium*, San Antonio, TX, March, 2004, pp. 22-25.

[26] N. Abatzoglou and S. Boivin, A review of biogas purification processes, *Biofuels, Bioproducts and Biorefining* 3 (2009) (1) 42-71.

[27] H. C. Shin, J. W. Park, K. Park and H. C. Song, Removal characteristics of trace compounds of landfill gas by activated carbon adsorption, *Environmental Pollution* 119 (2002) (2) 227-236.

[28] K. Y. Foo and B. H. Hameed, An overview of landfill leachate treatment via activated carbon adsorption process, *Journal of Hazardous Materials* 171 (2009) (1) 54-60.

[29] L. Sigot, M. F. Obis, H. Benbelkacem, P. Germain and G. Ducom, Comparing the performance of a 13X zeolite and an impregnated activated carbon for H2S removal from biogas to fuel an SOFC: Influence of water, *International Journal of Hydrogen Energy* 41 (2016) (41) 18533-18541.

[30] Song Chunshan and Wei Pan, Tri-reforming of methane: a novel concept for catalytic production of industrially useful synthesis gas with desired H2/CO ratios, *Catalysis Today* 98 (2004) (4) 463-484.

[31] J. C. Bruno, V. Ortega-López and A. Coronas, Integration of absorption cooling systems into micro gas turbine trigeneration systems using biogas: Case study of a sewage treatment plant, *Applied Energy* 86 (2009) (6) 837-847, doi: http://dx.doi.org/10.1016/j.apenergy.2008.08.007.

[32] Basrawi, Mohamad Firdaus Bin et al., Analysis of the performances of biogas-fuelled micro gas turbine cogeneration systems (MGT-CGSs) in middle-and small-scale sewage treatment plants: Comparison of performances and optimization of MGTs with various electrical power outputs, *Energy* 38 (2012) (1) 291-304.

[33] A. Colmenar-Santos, G. Zarzuelo-Puch, D. Borge-Diez and C. García-Diéguez, Thermodynamic and exergoeconomic analysis of energy recovery system of biogas from a wastewater treatment plant and use in a stirling engine, *Renewable Energy* 88 (2016) 171-184.

[34] P. Devlin, Demonstrating the business case for biogas-fueled stationary fuel cell power systems at wastewater treatment facilities, in: *Proceedings of the Water Environment Federation*, 2013, pp. 105-117.