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A Feasibility Study on the Waste-to-Biogas SOFC-Based Multi-Generation with Energy Storage System for Building Applications in China

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Abstract. The Waste-to-Energy Multi-generation system provides a feasible distributed waste recycling and energy saving solution for green buildings. However, the fluctuations in electricity demands and dynamic built environment obstruct its marketization. This study optimizes the existing waste-biogas-SOFC multi-generation configuration with energy storage systems. The research employs the operation data from an international airport in Southern China as a case study. The study compares the proposed system and that of previous SOFC-based systems in terms of economic and environmental benefits. The results show that the demand and supply of energy is balanced and higher energy efficiency and a significant reduction in the Greenhouse Gas (GHG) emission is achieved. The system presents a solid performance in payback and lifecycle cost (LCC) analysis and also satisfactory resistance to financial risks. Finally, this study draws the conclusion that the energy storage system could be utilized to optimize the existing SOFC multi-generation system.

1. Introduction

The rapidly growing world energy consumption has raised deep concerns over resource exhaustion and a series of environmental problems. The contribution from buildings has steadily increased, reaching 32% of global energy use and 19% of energy-related GHG emissions [1]. As the largest construction market, China adds 2×10^9 m² of floor space annually [2]. Thus, it is necessary to control indoor waste production and energy use in China. As an often-overlooked but significant fraction of MSW, food waste (FW) has great energy potential. Ni et al. [3] reported that SOFC servers are able to consume biogas-from-FW for electricity generation with high efficiency, limited environmental impact and the long lifespan. However, the electricity output of this system is strictly fixed and therefore, it cannot meet the dynamic energy demand in the built environment.

This paper first proposes an SOFC-based power generation system for converting FW into biogas. Different from conventional ones, the proposed system transfers recycled heat energy from off-gas to electrical energy directly and also be equipped with an energy storage system. The study not only reports the indoor applications of SOFC-based systems for green buildings but also aims to break the apparent contradiction between energy consumption and environmental protection. As less previous researches



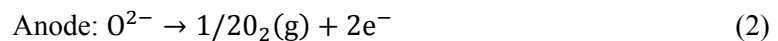
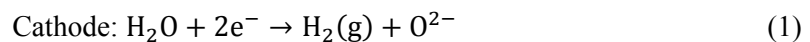
focused on the applications of indoor fuel cells or SOFC-based systems in China, this paper also utilizes operations data from a typical airport building in Southern China to analyse the feasibility of the proposed system by discussing its economic and environmental performances.

2. Literature Review of Solid Oxide Fuel Cells

SOFCs could provide clean electricity by electrochemically generation technology, showing an excellent higher efficiency than the conventional energy conversion systems. However, SOFCs require a higher operating temperature (i.e. 650°C–1000°C). This review will focus on the mechanism of SOFCs and applications in the distributed generation.

2.1. Mechanism of SOFCs

Each SOFCs stack is typically composited by three major parts: anode, cathode, and solid electrolyte to transport oxidized ions. In the Cathode part, oxygen is blown from the air and reduced on the surface of cathode material, and at the same time, the generated oxygen ions are carried by the solid electrolyte and oxidized on anode surface [4]. SOFCs are regarded flexible due to its availability to oxidize any fuels from anode materials such as hydrogen, hydrocarbons and even carbons into oxygen-ion, so that enables the control of plants size according to the required energy generation output [5]. The reaction taking place in the cell could be described by the following equations:



2.2. Application for electricity generation and modernization

Due to the challenge that grid load is not commonly constant and the electricity usage peak time largely relays on daily residential routine, the US's grid designs the capacity of electricity much exceeding the average amount of requirement to handle the one or two-hours-peak a year, leading to enormous energy loss [6]. To stabilize this large difference of electricity generation and usage, the distributed generation (GD) SOFC system enables flexible grids performance to generate energy and storage them inside power conditioning system for further usage at peak time.

Previous studies reported that by combining SOFC with the gas turbine hybrid system, high efficiency of 70% could be accomplished with excellent load following ability [7]. Another stationary application for SOFC has been established by Ballard Generation System with the capacity of 250kW to operate natural gas. America, Europe and Japan have established demonstration units and operated for a year achieving the cell voltage decay rate within 0.3% for every 1000 hours [8].

3. Proposed System Design

The overall system (shown in Figure 1) can be divided into three sections, biogas generation and treatment, biogas purification, and distributed energy generation.

3.1. Biogas Generation and Treatment

At the start of the whole system, a PAC grinder is used to compress the collected food waste. The concentrated waste is then sent to a digester, where it is further mixed and raw gas and digest is produced. Parts of the food waste inside the mixer is transported through a heat exchanger, where the water inside the heat exchanger will keep the food waste at a constant temperature. Sludge (human feces) is imported inside and the mixture is again treated inside the digester. Considering the possibility that there could be some general waste in food waste bin, a filter is installed before digest goes through a screw press. Liquid and solid parts are separated. Separated liquid is sent to an air pumped treater and exported from the system, while the remained solid is transported to a compost and recycled as fertilizer [9].

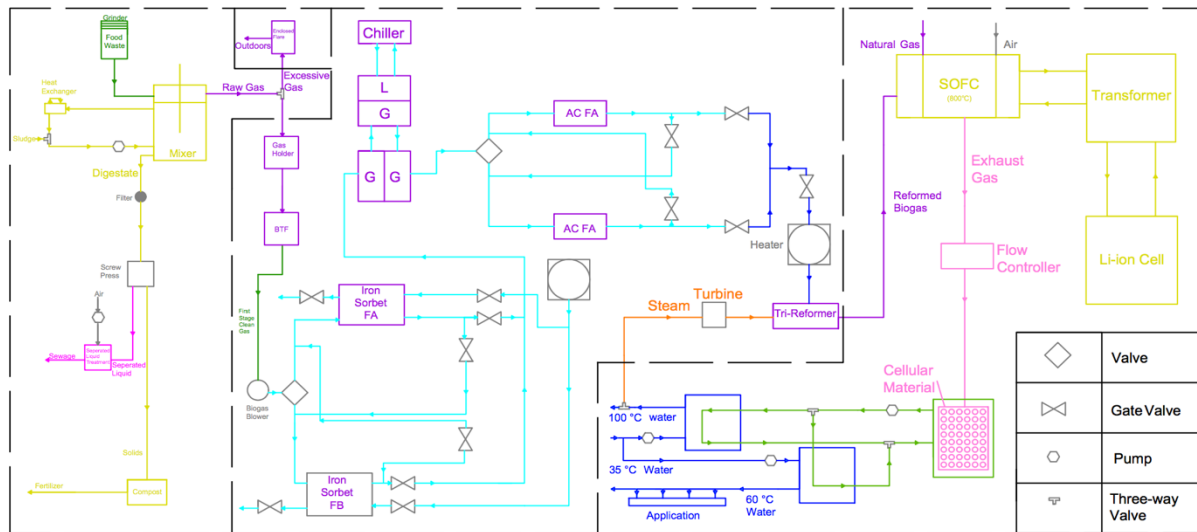


Figure 1. Proposed System Design (adapted from [9–10]).

3.2. Biogas Purification

After raw gas flowing out from the mixer, a flow control component is installed to divide excessive raw gas to an enclosed flare, where it is burned off and released. Remained raw gas goes through a gas holder into the purification process. Bio-trickling filter purifies the organic impurities [10] and the first-stage cleaned biogas goes through following stages to remove impurities like sulfur compounds, siloxanes and water. Clean biogas is then produced and enters a tri-reformer. Finally, reformed biogas is transported to distributed energy generation system to act as the energy source of the SOFC fuel cell.

3.3. Distributed Energy Generation

Considering the following case study section, the capacity of the SOFC servers is estimated to be around 1MWh. Therefore, the system selected to be the energy storage is required to cover the capacity. Other concerns in the proposed system are the cost of the energy storage and the efficiency of energy transformation. Taking these into consideration, Li-ion battery is adopted as the energy storage for the following case study, while other alternative energy storage systems would be discussed in the following section. The capacity of Li-ion cell is about 0.1–1MWh, with its high efficiency of 90% and low cost per kWh [11]. With the energy storage system, the electricity produced would be designed to be used in peak-time, which could increase the operating saving of the whole system.

Apart from the electricity generation part, waste heat recycling also becomes another energy generation subsystem. Exhaust gas (around 550°C) which carries a vast amount of heat can be regarded as another source of energy produced. A flow controller is installed to push the exhaust gas into a heat exchanger, where a porous ceramic material would help increase the efficiency of the cooling process. The coolant inside the green pipes carries the thermal energy of the exhaust gas to the next stage and the cooled exhaust gas is then released. Thermal energy extracted from exhaust gas is mostly used for providing hot water for domestic use. Two boilers (heat exchanger) is connected to pipes of the coolant. The first boiler heats water (35°C) to 100°C, and the second boiler heats water (35°C) to 60°C. Water from the first boiler goes to its application or is transferred as steam through a turbine to power Tri-reformer. As two boilers require different time duration to reach its designated temperature, the speed of the water flow is controlled.

4. Alternative Energy Storage Design Plans

Apart from the Li-ion battery, there are also some alternative energy storage design plans which are suitable for other cases and will be discussed in detail in this section.

4.1. Compressed Air Energy Storage

In this plan, the kinetic energy of the EG is recycled. The gas is first collected and compressed into a high-pressure tank. It then goes through a turbine to produce electricity. The electricity from both turbine and SOFC cell are connected to the domestic power supply line as an energy source. The efficiency of the system can reach 70% [12]. However, the thermal radiation could warm up the raw gas and affects the operation of the compressor. Thermal energy of the gas is also wasted under this system.

4.2. Steam Turbine Energy Storage

This energy storage system aims at storing the thermal energy of the EG. In this design, two layers of cooling fluid is used. Water is designed as the second-layer coolant, turning into steam and driving the turbines to produce electricity. Heat exchangers are also adopted to maintain the temperature of the steam to avoid gas explosion. This system removes dangerous chemical content and reduces the safety hazard. However, it has some drawbacks like leakage of water and requires constant maintenance.

4.3. Flywheel Energy Storage

The electric energy produced from SOFC is converted into kinetic energy by the flywheel. When energy output is required, flywheel slows down to release electric energy. Merits of this design are high feasibility, high efficiency (i.e. above 90%) and low maintenance cost. The operating environment of the system is also safe with normal pressure and temperature.

4.4. Pumped Hydro Energy Storage

Pumped hydro energy storage system can be combined with domestic water pipes to provide both electricity and water pressure. The electric energy generated from SOFC pumps the water up to a higher water tank. When energy output is needed, the water goes down and its potential energy turns into electricity. The efficiency of this system can reach between 70% to 85%. Meanwhile, as water and mineral ions inside are highly corrosive to metal, regular maintenance is needed.

5. Case Study: XG Airport

This section is to analyze the feasibility of the proposed system when applying to XG Airport, an important international airport located in Southern China. XG Airport covered an area of 1,255 hectares, serving over 102.9 million passengers annually. The total amount of recyclable waste is 41,950 kg/day.

5.1. Detailed Design of Proposed System

The hydraulic retention time is 20 days and the daily methane yield is 14.1L/kg VS. Through calculation, the methane production rate is 104.9 m³ CH₄/ m³day and the raw biogas production rate is 8,042.3 Nm³/day. Meanwhile, the production rate of solid waste fertilizer is estimated 16,000kg/day.

Therefore, a detailed design would be accomplished by adjusting the proposed system. Five PUXIN 260m³ digesters and three 2,000m³ gas holders in accordance with the previous statistics and two screw presses are required for solid-liquid separation. The production rate of biogas is 8,042.3 Nm³/day and the heat value of methane is around 35.7MJ/h. Therefore, the multi-generation is designed with five ES-5710 servers, providing electricity at 1,250kW uninterruptedly.

5.2. Economic Analysis

5.2.1. CAPEX and OPEX Analysis. The local government has financial support to encourage the energy performance improvement and could cover up to 50% of the total initial expenditure. Therefore, detailed valuation is shown in Table 1. Regarding the operation expense, monthly maintenance cost is estimated to be 1% of the total initial cost. In the biogas generation subsystem, the biogas production plant operational cost should be also considered, which is around \$2,900/month.

Table 1. Proposed system CAPEX and OPEX analysis.

	CAPEX (USD)	OPEX (USD)
Biogas Generation System	298,000	4,390/month
Biogas Treatment System	360,200	1,801/month
Power Generation System	4,841,000	24,205/month
Waste Heat Recycling system	520,000	2,600/month
Total	3,009,600 (50% subsidy)	395,950/year

5.2.2. Monthly Operation Saving Analysis. Considering the fuel cost adjustment and rent and rates special rebate, the final savings from SOFC electricity production is \$112,782. Similarly, the savings from water heating system and the result is \$7,320. Biogas generation plant provides another source of the savings: the solid-waste fertilizer. The price of this kind of fertilizer is around \$72.4/ton and 480-ton fertilizer could be produced monthly. Therefore, the total operation saving is \$154,858/month.

5.2.3. Payback Period (PP) Analysis. The interest rate is assumed to be =0.38%. Based on the statistics summarized before, equation (4) is used to calculate the PP.

$$PP = -\frac{\lg(1 - \frac{CAPEX}{Saving - OPEX} \cdot i)}{\lg(1+i)} \quad (4)$$

The payback period of the system considering the interest rate is slightly over 26 months. If 30% installation fee is added, the duration would extend to around 34 months and would be 73 months without government funding.

5.2.4. The LCC Analysis. The LCC of the system with only SOFC cell is calculated to make the comparison. In this part, equation (5) and (6) is adopted, where *SV* stands for Scrap Value, *n* stands for the 15-year lifespan of the SOFC system and *d* stands for 6.7% depreciation rate.

$$LCC = CAPEX + OPEX \cdot \frac{1-(1+i)^{-n}}{i} - SV \cdot \frac{1}{(1+i)^n} \quad (5)$$

$$SV = CAPEX[1 - (1 - d)^n] \quad (6)$$

When the system makes up of only an SOFC cell and its auxiliary components, the OPEX would drastically increase due to the price of natural gas which is adopted as the energy resource to substitute biogas. Considering the unit price of natural gas and fuel cost adjustment, the final cost of the fuel is \$1,403,169/year. With the maintenance fee of \$275,460/year, the total OPEX is \$1,678,629/year. Therefore, through the results shown in table 2, the LCC of the SOFC system would be reduced to a great extent when Biogas Generation-and-Treatment System and Water Heating System is added to the system design.

Table 2. The LCC comparison.

Parameter	Proposed System (USD)	Only SOFC System (USD)
CAPEX	3,009,600	2,295,500
OPEX	395,950	1,678,629
SV	1,946,110	1,484,348
LCC	6,933,636	25,324,264

5.2.5. Environmental Analysis. As a completely biogas-drive SOFC electricity generation cell and a waste heat recycling subsystem is proposed in the system design, the GHG emissions during the whole

lifecycle is minimized. This section analyzes the environmental impact of the system by comparing with natural gas based SOFC power generation and thermal power generation.

The lifespan of the SOFC is assumed to be 15 years. The life-cycle energy saving of SOFC part is 162,000MWh and that of water heating part is 11,779MWh. To achieve the same amount of energy, around 562,563 MMBtu is required for thermal power generation and 906 MMBtu for natural gas power generation when adopting reasonable transferring rates.

According to U.S Environmental Protection Agency [13], 95,900g CO₂/MMBtu, 11g CH₄/MMBtu and 1g N₂O/MMBtu is released from thermal power generation, while 53,060g CO₂/MMBtu, 1g CH₄/MMBtu and 0.1g N₂O/MMBtu conversion coefficient is adopted in natural gas power generation. Through calculation, GHG emission from thermal power generation is 53,779 tons of CO₂ equivalent, while traditional gas-based SOFC system releases 479 tons of CO₂ equivalent for 15 years. In contrast, the power input of the proposed system is waste-to-biogas generation system and accounts for no GHG emission.

6. Conclusion

The study proposes an eco-friendly SOFC-based building energy solution and verifies the economic and environmental feasibility of the proposed system. The system combines biogas-from-waste and the SOFC power generators, minimizing the environmental hazards caused by organic waste and also the fuel cost of the SOFC severs. In addition, the system also includes an energy storage system to meet dynamic built environments, which represents an innovative new possibility for the commercial use of SOFC in China. With regard to the first, the proposed system's annual financial savings of \$154,858 gives it a short PP (i.e. less than 27 months) and satisfactory resistance to financial risks. With regard to the second, the system can also significantly reduce the GHG emission, compared with the other existing systems. Therefore, it is anticipated that the proposed application can appropriately serve future infrastructure and building projects in China and beyond.

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