Economic Analysis of a Solid Oxide Fuel Cell Cogeneration/Trigeneration System for Hotels in Hong Kong

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ABSTRACT

Solid oxide fuel cell (SOFC) is promising for efficient stationary power generation. The high temperature waste heat from SOFC stack can be recovered for cogeneration/trigeneration. Due to the lack of relevant analysis on SOFC system in Hong Kong, this research is purposely designed to investigate the economics of a SOFC-absorption cooling cogeneration/trigeneration system for building application in Hong Kong. Energy consumption profile of Hotel ICON is adopted for a case study. Existing products of SOFC server and absorption chiller are chosen to configure the system. It is found that the payback period is less than 6 years with the Government subsidy at 50% of the overall system cost for a trigeneration system. Sensitivity analyses show that increases in the rate of electricity and the level of government subsidy increase the payback period of SOFC systems in Hong Kong. Besides certain technological difficulties, obstacles on the way to realize the proposed cogeneration/trigeneration system in Hong Kong are legal and social constraints and space limitation as well. This study highlights the suitability and the environmental impact of the SOFC-based multi-generation for building application in Hong Kong.

KEYWORDS: *Solid oxide fuel cell, Absorption Cooling, Cogeneration, Trigeneration, Hotel Energy Management, Hong Kong*

1 INTRODUCTION

Energy crisis has become an undeniable global issue. Not only countries as far as South Africa are plagued by electricity disruptions, rich states also face periodic blackouts and become increasingly concerned with power supply security [1]. In China, the Electricity Council estimated a power deficit of 40 GW in 2012 [2], and the coal shortage has been considered as the core issue in restricting the power supply [3]. Due to the limited indigenous natural resources, Hong Kong heavily relies on energy import from Chinese mainland and overseas countries, which consequently makes Hong Kong vulnerable to external energy interruption. In terms of the distribution of energy consumption, according to the Environment Protection Department (EPD), the Government of Hong Kong Special Administrative Region (HKSAR), over 50% of local power supply was originated from coal, and about 23% was from gas in 2009 [4].

To address the energy crisis, there are two options: 1) searching for alternative energy sources; 2) increasing the energy conversion efficiency thus reducing the energy demand. Given the greenhouse gas effects caused by burning fossil fuels, many efforts have been made to utilize renewable energy resources, such as solar and wind power. Conventional power generation systems have an average efficiency of about 30% due to the Carnot efficiency limit and the majority of energy is wasted in the form of heat. Cogeneration, or combined heat and power (CHP) generation system, can effectively increase the system efficiency up to 80% as the waste heat from the power plant is utilized for heating or cooling production (i.e. use an absorption chiller). Apart from the fossil fuel-fired power generation, fuel cells have emerged as promising energy conversion devices due to their high efficiency, quite operation, and low emission. In particular, solid oxide fuel cells (SOFC) are very promising for combined heat and power co-generation and thus are suitable for building applications. Compared with low temperature fuel cells, the high temperature (i.e. 800^{o}C) SOFCs exhibit several advantages: (1)

fast electrochemical reaction rates; (2) low cost catalyst; and (3) fuel flexibility. Due to their distinct features, extensive efforts have been made to develop efficient and reliable SOFCs systems capable of using various alternative fuels (i.e. conventional natural gas and renewable biofuel) for a variety of applications [6-8]. In order to improve the long-term stability of SOFC and decrease the cost of SOFC system, there is a trend to lower the operating temperature of SOFC [9]. At reduced temperature, the catalyst sintering can be greatly inhibited and low-cost materials can be used. However, the SOFC performance decreases with decreasing temperature as the ionic conductivity of conventional SOFC electrolyte and activity of SOFC cathode decrease with decreasing temperature. To improve SOFC at reduced temperature, alternative cathode materials have been developed [10, 11]. It is found that by fabricating nanostructured electrode, the reaction sites can be enlarged significantly [12]. Ceria-based materials showed high ionic conductivity at reduced temperature and thus are promising alternative electrolyte materials for SOFCs [13]. Previous study showed that fuel cells for residential cogeneration would be able to reduce carbon dioxide emissions by up to 49%, nitrogen oxide emissions by 91%, carbon monoxide by 68% and volatile organic compounds (VOC) by 93% [5]. Whole building energy simulation suggested that when applied in commercial buildings, an optimized SOFC cogeneration system is able to decrease the CO_2 emission by 50% [14].

In Hong Kong, building is the biggest energy consumer and air-conditioning accounts for almost 30% of the total electricity consumption in 2010 [15]. Although comprehensive studies of fuel cell based cogeneration systems have been conducted in North America, European countries and other developed societies [16-18], there is no study on SOFC-based combined power and cooling system for Hong Kong. To fill this research gap, this study aims to investigate the potential of SOFC absorption cooling based cogeneration/trigeneration system for building application in Hong Kong. The energy consumption data for Hotel ICON is used in a case study for economic analysis. Commercial SOFC product and absorption chiller are adopted. The initial cost, operation and maintenance cost, as well as the government subsidy are considered in the payback period analysis. Sensitivity analyses are conducted to evaluate the uncertainties in reality. In addition, interviews with stakeholders and professionals in this field are arranged to understand the social and technical issues for the proposed system.

1.1 Cogeneration / Trigeneration Systems

The World Alliance for Decentralized Energy [19] defined cogeneration as "the process of producing both electricity and usable thermal energy (heating or cooling) at high efficiency and near the point of use". The efficiency of a cogeneration system is measured by the percentage of the input fuel that can be utilized as power or heat. It is generally expressed in electrical efficiency ($\eta_{(electricity)}$) and overall efficiency ($\eta_{(overall)}$):

$$\eta_{(electricity)} = P_{(electrical)} / FI \qquad (1)$$

$$\eta_{(overall)} = [P_{(electrical)} + P_{(thermal)}] / FI \qquad (2)$$

where $P_{(electrical)}$ and $P_{(thermal)}$ are the electrical output (kW) and useful thermal output (kW) and FI stands for the fuel input to the system (kW).

A trigeneration system is regarded as an advancement of the cogeneration system. It further recovers the residual energy, commonly used to provide hot water. The overall system efficiency is therefore defined as:

$$\eta_{(overall)} = [P_{(electrical)} + P_{(thermal)} + P_{(hot\ water)}] / FI \qquad (3)$$

The most widely used technologies for electricity generation are reciprocating internal combustion engine, micro-turbine, Stirling engine and fuel cells. Performance comparison between cogeneration systems based on different conversion technologies indicates that the major advantages of fuel cells are their high performance and low emission. For example, the nitrogen oxide generated from fuel cell is as low as 1-2 ppmv at 15% oxygen, whilst the value for the commonly used reciprocating internal combustion engine can reach up to 1800 ppmv [14].

In comparison, conventional heat engines requires several steps for power generation, including combustion converting chemical energy of the fuel into thermal energy, which is then used to drive turbines for power generation via a generator, whereas fuel cell based cogeneration/trigeneration produce electrical power from electrochemical reaction directly hence is characterized by fewer system components. This results in low maintenance and low running cost. In addition, the fuel cell system generates power in a quieter manner, reducing the noise level.

1.2 Fuel Cells

Fuel cells can be categorized according to their operating temperatures. Low temperature fuel cells generally refer to the units operated below 100°C (e.g. Alkaline Fuel Cell, Direct Methanol Fuel Cell, Polymer Electrolyte Membranes Fuel Cell) while the high temperature fuel cells typically work at 400-1000°C (e.g. Molten Carbonate Fuel Cell and Solid Oxide Fuel Cell). In particular, high temperature SOFC has greater potential for cogeneration application [14]. Its fuel flexibility eliminates the need of reformer and the technical difficulties in hydrogen production and storage. SOFC is able to utilize a wide variety of catalyst materials, lowering the cogeneration system cost. The solid electrolyte of SOFC also provides advantage for the stationary operation in building cogeneration systems [20].

1.3 Absorption Cooling

Absorption chillers utilize heat rather than electricity as an energy source. Currently two types of mixture are widely employed as refrigerants in absorption cycles. One is the water ammonia mixture and the other is the lithium bromide-water mixture, also known as an aqueous LiBr mixture [21]. While the former is capable of providing temperature below freezing point and is normally adopted in food refrigeration applications, the LiBr mixture is able to chill water to 4°C -38°C hence is commonly used for building air-conditioning [22]. Similar to the traditional vapor-compression cycle, absorption cycle also consists of condenser, expansion valve, and evaporator, but replaces the compressor with a physical cycle taking place between the absorber, pump and regenerator [23]. For absorption chillers adopting lithium bromide-water mixture, water is used as a refrigerant. External heat source is first used to boil the water out of the solution and maintain the vapor to at a high pressure. As the condensing temperature of the vapor is higher than the ambient temperature, refrigerant condenses in the condenser and releases heat. The high-pressure liquid water then passes through a throttling valve that reduces its pressure, which in turn decreases the boiling temperature of the refrigerant. Low pressure water then flow into the evaporator, where it is boiled at a low temperature and pressure and absorbs heat from the refrigerated space or water (for chilled water production in a central air conditioning system).

Compared with the compression cycle, major advantages of the absorption cooling system come from two aspects [24]: 1) the absorption cycle requires thermal energy input for increasing the refrigerant vapor pressure by boiling water out from the absorbent thus waste heat from the industry or from the power plant can be utilized; 2) the absorption cycle employs refrigerants of low Global Warming Potential, whilst the vapor compression cycle commonly uses halocarbon compounds that are known to be ozone depleting. However, it should be also noted that the coefficient of performance (COP) of absorption chiller is generally lower than that of electric chiller based on vapor compression cycle. The absorption chiller is usually more space demanding and heavier than conventional vapor compression chillers. In addition, there is risk of toxicity if ammonia absorbent is adopted [23]. Despite of these possible disadvantages, the absorption chillers are preferable when substantial amount of waste heat is readily available.

2 SOFC Cogeneration/ Trigeneration System

2.1 Selection of Premises

The suitability of the proposed SOFC-absorption cooling multi-generation system is evaluated based on two criteria: 1) electricity demand should be relatively constant in daily basis, as the SOFC energy server will operate uninterruptedly for the sake of long-term durability; 2) preferably there should be stabilized demand for space cooling and hot water (if trigeneration), as the power generation and the provision of cooling and/or hot water are simultaneous.

Due to the fact that most people leave home for work or study during the daytime and return home after the office hours, residential buildings, office towers, shopping malls and industrial blocks suffer from significant fluctuation in power and cooling demand within a day. This limits the applicability of the cogeneration system in these buildings. The same applies to institutional buildings. On the other hand, hotels, hospitals and transport buildings (e.g. airport terminal) are of higher suitability given their non-stop operation and substantial requirements in power, cooling and/or hot water. According to the Hong Kong Tourism Board [25], there are about 200 hotels offering over 60,000 rooms and more than 600 guesthouses in Hong Kong in

2011. The significant amount of hotels enhances the potential of wide application for the proposed system. Therefore, a hotel is chosen for the case study of the system economics.

2.2 Subject of Study – Hotel ICON

Hotel ICON was officially opened in September 2011. There are three restaurants, 262 guest rooms in various types, spa facility, swimming pool and health club in the hotel [26]. Hotel ICON stands as a stylish hotel, providing comprehensive services and facilities. It is popularly regarded as a fashion of the modern hotels in Hong Kong hence it is chosen for investigating the applicability and the prospect of this SOFC-based energy system. In view of the scale and the sophisticated facilities in the hotel, a trigeneration system providing electricity, space cooling and domestic hot water is considered of higher applicability than a cogeneration system. This can be justified through the discussion on system economics elaborated in Section 3.

According to the Utility Consumption Report of Hotel ICON from January 2012 to December 2012, the hotel consumed 12.26GWh electricity in year 2012, bringing in a total electrical charge of US$1.44M [1]. This equals to an average hourly consumption of about 1.4MWh at the rate of US$0.118 for each unit consumed. The electricity consumption profile of the hotel is shown in Fig. 1.

In general, the electrical energy consumption varied with the seasons. The consumption experienced the lowest level (slightly over 0.73 GWh) during winter; then grew significantly and reached the peak value of over 1.2 GWh per month in summer. Similarly, the average hourly power consumption fluctuated throughout the year – being the highest value in June, exceeding 1.7MWh and decreasing afterwards to the end of the year.

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1 Based on USD/HKD exchange rate of 7.77 on 9 Nov 13 (HSBC).

2.3 System Configuration

The core component of this cogeneration/trigeneration system is the SOFC server for electricity generation, and the exhaust heat will be recovered by an absorption chiller using lithium bromide as absorbent and water as refrigerant. Conceptual system arrangement is shown in Figure 2 and 3.

As this study focuses on systems for large-scale application instead of single-family use, SOFC unit with higher capacity is considered. The leading manufacturer in this field is Bloom Energy in the United States. Their recent installations include a 4.8MW system for Apple's new data center in Maiden, North Carolina and a 6MW system for eBay's data center in Utah, which was fully functional in mid-2013 [27]. The largest energy server commercially available from Bloom Energy is the ES-5700 with a capacity of 200kW and is adopted for the case study [27]. Given the fuel input at 387kW for a base output of 200kW, an average electrical efficiency of 51.7% can be expected [27]. Referring to the power consumption profile of the Hotel ICON in 2012, the Hotel consumed the least amount of electricity in February (779MWh), requiring power supply at a rate of 1.12MW [26]. Therefore, the proposed cogeneration system consists of five units of 200kW ES-5700. The electrical energy demand exceeding the SOFC capacity will be supplemented by grid power supply.

For absorption cooling, the chillers are generally categorized as single effect, double effect and triple effect chillers. The efficiency of the chillers is measured by the Coefficient of Performance (COP), which is defined as the ratio of refrigeration output to the net thermal power input. The New Buildings Institute [28] pointed out that the COP is relatively low for single effect chillers, which operate on low-pressure exhaust (138kPa or less) or hot water between 85°C - 90°C [24], and the COPs are limited to approximately 0.5-0.7 only. On the other hand, a double-effect cycle contains a pair of additional generator and condenser that increase the amount of refrigerant vapor. These chillers use high-pressure steam as heat source so that the cooling capacity of the chiller and the overall system efficiency is enhanced. As a result, the COP of double-effect absorption chillers can reach 1.0-1.2. Triple-effect system is a further advancement of the absorption cooling system. However, unlike single and double-effect chillers, industrial review points out that it is still on the stage of small batch commercialization [29].

Considering the technological maturity and market availability, a double effect chiller is adopted for the proposed system. One of the leading manufacturers in the field of non-electric chiller is the Broad Group in China. It has the largest market share in China, America and Europe, and it owns patents of a number of leading technologies for heat recovery and indoor air infiltration [30]. Therefore, Broad X Non-electric Chiller is chosen and the exhaust flow rate is calculated by Eq. (3) and (4) as follows:

$$\dot{Q} = c\dot{m}\Delta T \tag{4}$$

$$\dot{m} = \frac{c\Delta T}{\dot{Q}} \tag{5}$$

$\dot{m}$ refers to the mass flow rate of the substance (m^3/hour); C refers to the specific heat capacity of the substance (kJ/(kg·K)); $\dot{Q}$ refers to the total hourly energy consumption (kJ); ΔT refers to the temperature difference experienced (K).

Assuming the energy server box is thermally enclosed, the residual energy in steam and carbon dioxide mixture is directed to a desired temperature of 500°C by controlling the flow rate. It is assumed that no energy is lost to the environment in this process. Based on Eq. (4), the exhaust gas at 500°C as input to the absorption chiller flows at about 4,128kg/hour, which is capable of driving a Broad X Non-electric Packaged Hot W/Exhaust Chiller to provide cooling at 630kW.

Apart from the SOFC energy server and the absorption chiller, the proposed system also requires a series of auxiliary components. As the Bloom Energy Server is designed with output of 480V, 60 Hz, 3 or 4 wires 3 phases for American users, a transformer is needed to supply power at 220/330V, 50Hz, 3 or 4 wires 3 phases for Hong Kong's condition. Considering the well-developed electrical transformation technology, no energy loss is considered for this stage. Secondly, the high operating temperature of SOFC units requires significant amount of start-up energy. In order to enhance the system efficiency, the SOFC-based cogeneration/trigeneration system is designed to operate continuously at constant power output level. In view of the fluctuating power demand during the day in reality, rechargeable battery storage is installed in the system to store the excessive power supply when demand is low and supplement the supply during peak hours. In addition, the SOFC works at a high temperature (i.e.900-1000°C), which raises technical difficulty on temperature tolerance for the system components in the downstream. To reduce the cost of materials and match the SOFC exhaust gas with the absorption chiller, a flow controller with valves is added to level the temperature of the exhaust to 500°C, which is the required temperature of the absorption chiller. The flow controller is considered as thermally insulated.

The listed above form a SOFC-based cogeneration system, which exhausts hot gas mixture at the temperature of 160°C, leaving considerable thermal energy unused. As the selected hotel requires noticeable space cooling and hot water throughout the day, a heat exchanger is added to recover the residual thermal energy from the absorption chiller to provide domestic hot water for trigeneration purpose. Considering the availability of highly efficient heat exchanger in the market, the energy loss at this stage is assumed to be 2%. Trigeneration system arrangement is outlined in Figure 3.

3 SYSTEM ECONOMIC ANALYSIS

For comparison purpose, cost and benefit analyses are performed on both the cases of cogeneration and trigeneration. The system with more competitive payback will be further considered for seven potentially influential factors, in order to investigate the consequence caused by single-factor changes as well as the combined effect.

3.1 Cogeneration System Costs

According to the report from Energy & Capital [31], the largest private fuel cell project, Apple's 4.8 megawatts fuel cell farm in North Carolina, requiring 24 ES-5700 units, was built at a cost of US$ 6.7M. The figure indicates a unit cost of US$ 1.34 million. The CEO of Bloom Energy mentioned in an interview with the 60 Minutes of the Columbia Broadcasting System, that the ES5000, with power output rate at 100kW, was offered at a quoted price of US$ 0.7M – 0.8M. The CEO also expressed the company's confidence in the mass production of the ES-5700 with the doubled capacity at around the same price of ES-5000. The company was also expecting popularization of the small units (1kW) for residential use, at the cost less than US$ 3,000 within the next five to ten years. Given the above information, it is reasonable to take the unit price of ES-5700 energy server at US$ 1M in this study.

For the absorption chiller, the quoted price was RMB 1.42M in 2011 [31]. The price was based on a chiller fueled by natural gas or liquefied petroleum gas; a 1.5% increase is required when the chiller is fueled by town gas or landfill gas. The given price covers all the items on the supply list, including the chiller, pump set system, the enclosure, as well as the cost of lithium-bromide/water solution, system commissioning, and two years warranty. In addition, a

5% inflation rate is considered for the price adjustment hence the cost of the absorption chiller is calculated as about US$ 260,500[2].

Apart from the energy servers and the packaged absorption chiller, a sum of 20% on costs of energy servers and absorption chiller is assumed for all the remaining system components in consideration of the complexity and the safety assurance for the overall system.

Previous installations of the Bloom Box were mainly for companies with facilities in California, the USA, in order to be qualified for the subsidies. According to the company's sales representative, the purchase cost of the system and the related project can be reduced by 80% through Federal and California State Taxpayer subsidies and utility ratepayer subsidies and rebate [32]. In Hong Kong, although there is no specific subsidy for SOFC or cogeneration application at present, the city has been putting increasing attention on carbon reduction and sustainability. The Government's concerted efforts include the Greening Master Plans since 2004 [33], the Pilot Green Transport Fund [34]. At the same time, the Government has been encouraging innovations and technologies on renewable energy. A US$26M funding was set up in 2010 for an R&D Cash Rebate Scheme. Another example of governmental support on green technology is the Hong Kong Science Park, where green technologies and precise engineering have been applied to a considerable scale. According to the Electrical and Mechanical Service Department (EMSD) of HKSAR, there have been numerous government-funded renewable energy projects [35] for wind turbines and photovoltaic panels. Although there is no existing government funded cogeneration/trigeneration project in Hong Kong, the EMSD has been actively promoting combined heating and power generation. Given the above, it is expected that supporting policies and subsidies will be implemented and granted once the technology matures and the appliances become locally available. Therefore, government

[2] Based on USD/RMB exchange rate of 6.10 on 9 Nov 13 (Bank of China).

subsidy at the level of 50% system cost is perceived as reasonable for demonstration projects of SOFC-based cogeneration in Hong Kong.

3.2 Cogeneration Operational Costs

The operational costs of the proposed system consist of three parts: the gas fuel cost for the SOFC energy server, the electrical charge for the absorption chiller and conventional air conditioning system (to supplement the absorption chillers) and the maintenance cost.

According to Bloom Energy, although the ES-5700 server is specified with natural gas, the energy server is highly fuel flexible that allows it to run on other gas fuel with similar composition. In Hong Kong, town gas is the most widely used gas fuel thus it is considered for SOFC energy server. According to the town gas tariff in 2012 and the fuel requirement of each server, the monthly fuel cost for the five ES-5700 energy servers amounts to about US$27,140.

Even though the absorption cycle utilizes heat as major energy source, it still consumes a minimal amount of electricity for the operation of auxiliary components in the chiller (e.g. pumps). As specified by the manufacturer, the Broad X Non-electric Packaged Hot W/Exhaust Chiller requires power supply at 4.3kW, which amounts to a power consumption of 3,096kWh/month. The China Light and Power Company (CLP) has a larger market share in Hong Kong, serving 2.35million customers by the end of 2010 while Hong Kong Electric Company had less than one fourth of that amount [36]. For this reason, CLP's tariff rate is adopted for further economic analysis. The monthly electrical cost based on non-stop and steady operation of the absorption chiller is US$453.

Due to the high start-up energy requirement, the SOFC based cogeneration system is designed to operate uninterruptedly. The continuous operation inevitably demands stringent maintenance for quality and safety assurance thus considerable amount should be budgeted for inspection and restoration. Consultation with professionals in building services engineering and building maintenance suggested annual maintenance cost at 4-8% of the overall system cost as a rule of thumb. Therefore, an annual maintenance cost at 6% of the total system cost is set aside for maintenance, which adds another 0.5% of the system cost to the monthly operational costs.

3.3 Multi-generation Operational Savings

At the rate of 200kW, the five ES-5700 energy servers are capable of generating a total of 8.76GWh annually, equivalent to roughly 720MWh per month. Under CLP's Bulk Tariff rates [37], assuming Maximum Billing Demand to be 650 kVA for the Hotel, the Off-Peak Period (daily between 2100-0900 hours and all Sunday and Public Holidays) is taken as 408 hours per month, the On-Peak period (all other hours) is taken as 312 hours, the total electrical charge savings (compared with existing power and cooling supply of Hotel ICON) from the power generation by SOFC energy server amounts to about US$0.77M.

The existing chillers in the Hotel ICON consist of three large-scaled Carrier Evergreen Centrifugal Chiller model number: 19XR05004201 REV B and one smaller Carrier Chiller model number: 30HXC345A-HP1. Nominal cooling capacity for the first three chillers is 2.46MW with a rated power input of 425kW, whilst nominal cooling capacity for chiller 4 is 1.18MW with a rated power input of 264kW. In view of the fourth chiller being mainly for standby use, the estimated COP value of 5.79 for the Evergreen Chillers is adopted to scale the electrical savings through absorption cooling. As discussed in the section of system configuration, the simulated absorption chiller is capable of cooling the space at the rate at 630kW. For an electrical chiller of the same cooing capacity and COP, it requires power supply at 109kW and the monthly power consumption for continuous operation amounts to

78.5MWh. The monthly savings on electrical charge by absorption cooling at CLP's Bulk Tariff reaches US$8.42M.

Given the above, the baseline costs and savings for cogeneration system are listed in Table 1. The initial appraisal indicates that the system should be able to break even by the end of the 10th year given that 50% of the system cost is subsidized.

3.4 From Cogeneration to Trigeneration

The trigeneration system is an advancement of the cogeneration system, with the same energy server units, absorption chiller, auxiliary flow controller and cell storage but added with a heat exchanger. Compared with the cost of SOFC, the cost of thermal exchanger and related pumping work is relatively insignificant. Therefore, the total cost of auxiliary components is revised from 20% to 21% of the sum of the energy serves and the chiller.

For the trigeneration system, the operational costs remain unchanged, whilst the additional saving on the gas fuel by means of hot water production is obtained. Existing hot water heating system in Hotel ICON for domestic hot water supply adopts the Blue Flame NJW321FEL Commercial Heating manufactured by Towngas. The specifications of the boiler indicate the efficiency is around 84.3% at the highest gas consumption (238MJ/hour) to supply 32 liter hot water per minute at 25°C temperature rise. The following assumptions are made in calculating the hot water production from the heat exchanger in the proposed system:

- Exhaust flow rate: 4,128kg/h
- Specific heat capacity of the exhaust: 1.70 kJ/(kg·K)
- Specific heat capacity of water: 4.18 kJ/(kg·K)
- Temperature of the exhaust inflow to exchanger: 160°C
- Temperature of the exhaust outflow from the exchanger: 60°C

- Temperature of water inflow to the heat exchanger: 20°C
- Temperature of water outflow from the exchanger: 45°C
- Water density: 1liter/kg

Energy flow rate from the exhaust to domestic water based on Eq. (3) is 687.7MJ/hour.

Hourly domestic hot water production by Eq. (4) is 110 kg/min, equals to 110 liter/min.

The production of 110 liters per minute hot water at 25°C temperature rise equals to 3.44 units of the Blue Flame NJW321FEL water heaters, which consume 818.7MJ/hour gas fuel.

The amount of town gas saved by hot water production = 818.7MJ/hour * 720 hours/month = 589.5GJ/month.

The saving on the gas bill given the current tariff rates = US$20,640

Similar cost-and-benefit analysis is performed on the trigeneration system, which shows that the payback period of trigeneration system is within 6 years under the baseline condition, 40% less than that of a cogeneration system discussed above. The results suggest a higher market potential for the trigeneration system for commercial application in hotels in Hong Kong.

From the perspective of energy utilization, the breakdown of system inputs and outputs is summarized in Table 4. As defined in Eq. (1) (2) (3), both systems have an electrical efficiency of 51.54%; the overall system efficiency for cogeneration is 84.02% whilst that for trigeneration is 93.86%, the system efficiency is improved by 9.84% when adding the heat exchanger for domestic hot water production.

3.5 Trigeneration System Sensitivity Analyses

In regard to the uncertainties behind the assumptions made in compiling the baseline profile, 10% variation in the cost of the SOFC energy server, absorption chiller, auxiliary components, level of government subsidy, unit price of fuel and electricity as well as maintenance cost will be considered for the sensitivity study. Considering that the cost of cell storage may vary significantly for different capacity and storage method, and the cell storage accounts for the majority of the auxiliary cost, +10% increase in the cost of auxiliary components refers to a change from 21% to 31% of the sum cost of the SOFC energy servers and the absorption chiller. Similarly, 10% variation of the auxiliary components refers to a cost drop to 10% of the sum cost of SOFC energy servers and absorption chiller. It should also be noted that +10% increase of the government subsidy refers to the increase of subsidy level from 50% to 60% of the total system cost, whilst 10% decrease of the subsidy indicates the level of subsidy is reduced from 50% to 40%. The results of sensitivity analysis for the proposed trigeneration system are presented in Table 2 and Fig. 4.

It is found that an increase in the government subsidy and the electricity cost helps elevate the feasibility of the cogeneration system. 10% increase in the grant and in the rate of electricity can shorten the payback period by at most one fifth. On the other hand, an increase in the price of the energy server and the auxiliary components may adversely affect the payback by around 15%; 10% growth in the maintenance expense will also prolonged the period by over 7%. Despite the absorption chiller being the second major component in the system, the effect on feasibility by varying its price is negligible.

3.6 Trigeneration System Optimistic and Pessimistic Analyses

In order to examine the combined effect of these factors, further optimistic and pessimistic analyses are conducted. In the optimistic case, government subsidy is set at 60% of the total system cost and a 10% increase is assigned to the cost of electricity, whereas the costs of energy servers, absorption chiller, auxiliary components as well as the gas fuel and maintenance are deducted by 10%. On the other hand, a pessimistic scenario is where the government subsidy shrinks to 40% of the total system cost, electricity is devalued by 10% and all other factors considered are raised by 10%. Results of the extreme cases are presented in Table 3. While single factor affects the payback period by 22% at the most, time required for the operational savings to compensate the initial cost can be more than doubled if adverse changes occur altogether, lengthening the payback period to almost 14 years. Similarly, in a most favorable circumstance, it is possible for the payback period to be halved, leaving less than 2.8 years for the initial investment to be financially justified.

In view of the 10 years warranty given by the manufacturer of the energy server and the 25 years of designed life span of the absorption chiller [38], a payback limit of 10 years should be considered acceptable. With regard to the common practice of achieving break-even within 5 years in building design, the system is of great potential in financial feasibility given most of the results from sensitivity analysis align within 4-7 years.

4 INTERVIEW AND CONSULTATION

In order to include other influential factors for the prospect of the SOFC-absorption cooling based cogeneration/trigeneration system, interviews were arranged for inputs from different perspectives, including the research/academic professors in the field of multi-generation and renewable energy, engineering consultant for low carbon technologies, senior professional with a role in governmental committee as well as the end-user's representative. Questions raised during the interview mainly focus on their concerns on the technology of SOFC and cogeneration/trigeneration, their opinions towards the prospect of SOFC-based cogeneration/trigeneration in Hong Kong and distributed power generation in a broad sense, the possibility of obtaining government support for SOFC and the combined power and cooling/heating system. Key points are highlighted and summarized in the next section.

4.1 Technical Difficulties for Cogeneration System

The major difficulty in technology lies in SOFC. Although the Bloom Energy SOFC server is commercially available with several large-scale existing projects, there is a lack of informaiton for the actual performance and the lifespan of SOFC remains to be demonstrated. Without actual operational record, the manufacturer's specification is less convincing. In Hong Kong's setting, the gas fuel is likely to be town gas instead of natural gas, where the composition may not be consistent and the effects of changing fuel type need to be verified by actual operation. Since there are only a few companies capable of manufacturing large capacity SOFCs, the reliability of the product requires further investigation.

In addition to the immature technology, considerations should also be given to the operational strategy under fluctuating and disproportional electricity, cooling (and hot water) demand. As agreed with the previous studies on the similar content, the proposed system possesses shortcomings as it requires as few on/off operations as possible due to the high start-up energy [39]. The system is currently unable to serve as a complete substitute to the conventional system as it supplies at constant rate, thus may encounter difficulties in balancing between peak demand and excessive supply, or satisfying power and cooling at the same time.

4.2 Legal Constraints for Cogeneration/Trigeneration

More than one interviewee has indicated that, the private power generation is currently a legal offence in Hong Kong. Consents have to be obtained from both the Government and the power companies before operating the proposed system for power generation.

To encourage cogenration/trigeneration application, connection to national or municipal grid for selling back redundent electricity is found to be a popular practice in European countries such as Germany, Belgium and Spain [40], which in turn helps alleviate the burden on the grid. However, there is no such policy in Hong Kong at present, as private power generation is prohibited, providing no additional incentive to install the proposed system.

4.3 Government Support for Cogeneration/Trigeneration

All interviewees agreed that it is possible for the cogeneration/trigeneration system to obtain certain Government support in forms of promotion, subsidy or funding. However, researchers also expressed that the Hong Kong Government has been rather conservative in granting funds in order to be responsible for taxpayers. Only technologies with sufficient demonstrations and proved benefits can be qualified. Application for such support requires high confidence and solid evidence in electrical savings and carbon reduction. Before promoting the cogeneration system to the market, small-scale demonstrations and experimental projects could be helpful.

Nevertheless, large-scale commercialization heavily relies on cost competitiveness in the market. It is for this reason that the cost of cogeneration system, in particular the cost of SOFC energy server has to be trimmed down noticeably.

4.4 Additional Concerns for Cogeneration/Trigeneration Installation

From the users' point of view, a short payback period within 3 to 5 years seems to be a necessity for the adoption. Very few building developer can afford payback period longer than 5 years. Apart from energy cost savings, currently there is no additional incentive for owners to adopt green technologies, since most green building schemes are voluntary and point based.

A practical concern for installing the cogeneration system is the space limitation. Although the energy servers are much smaller in size compared with conventional power plant, there is little space for on-site power generation for buildings in Hong Kong, especially commercial buildings. At the same time, the power capacity and cooling supply from the cogeneration system sometimes may not match the actual demand in buildings, additional electrical chillers or grid power may be in need to supplement the supply during peak hours. Installation of cogeneration system without completely abandoning the existing system may be considered as uneconomical.

5 CONCLUSION

The emergence of SOFC based cogeneration threw lights on the global energy crisis. Literature review reveals that the current applications of these systems are limited to micro-cogeneration for single-family use. Studies have been conducted for SOFC based cogeneration in North America, Europe, Australia and Japan but no such research targets at the natural and social environment in Hong Kong. In this highly populated metropolitan city, buildings account for a remarkable amount of total energy consumption, among which the largest percentage is contributed by air-conditioning in buildings. This study is set to investigate the prospect of the SOFC based cogeneration/trigeneration system from both internal (e.g. cost and benefit, technical concern) and external aspects (e.g. legal constraint and social support) in hope of searching for a new solution to enhance building energy performance.

Hotel is selected as the target application area after comparing the energy and cooling demand patterns among major types of buildings in Hong Kong. In order to enhance the practicality of the study, Hotel ICON is approached for their energy consumption profile in 2012 for case study on system economics. Given the subtropical climate in Hong Kong, unlike the conventional cogeneration system for power and space heating, the proposed system consists of absorption chiller to convert the exhaust heat for space cooling and is designed to operate around the clock, providing 630kW cooling and 1000kW electricity to the hotel uninterruptedly.

Based on steady state analysis, the cogeneration system is found to have payback period of around 10 years. The overall system efficiency can be further enhanced from 84% to 94% by transforming the cogeneration system to trigeneration; the latter produces hot water alongside with power and cooling for the users. Similar calculations are performed on the trigeneration system and generate a promising baseline payback period of 5.7 years. The payback period could be shortened if the higher subsidy is granted and/or the unit price of electrical power climbs. On the contrary, it is adversely affected by the cost of the energy server, the chiller, the auxiliary components, maintenance as well as rate of gas fuel. The payback period for the proposed trigeneration system varies from 2.7 to 13.9 years in extreme conditions, and generally fluctuates around 4 to 7 years under single factor influence, which gives considerable market potential for the proposed trigeneration system.

Through interviews with professionals in the related fields and end user's representative, concerns are raised with regards to the technical difficulties of the system, the legal constraints and the practical installation difficulties. In summary, the prospect of this SOFC-absorption cooling based cogeneration/trigeneration system relies on: 1) technological development to enhance the reliability and affordability of SOFC units for commercialization; 2) governmental support in the starting stage; 3) demonstration and educational projects to strenghthen pulic awareness of cogeneration/trigeneration; 4) liaison with the power companies and the Government to mitigate legal constraint in order to realize distributed power generation and grid connection.

If the above aspects are all addressed, large-scale SOFC-absorption cooling based cogeneration/trigeneration system is promising for building applications in Hong Kong.

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List of Tables

List of Figures

Table 1 Costs and Savings Baseline Profile for Cogeneration and Trigeneration System

	Cogeneration	Trigeneration
System Cost	Amount (US$)	Amount (US$)
SOFC Energy Server	5M / 5,000,000	5M / 5,000,000
Absorption Chiller	0.26M / 260,497	0.26M / 260,497
Auxiliary Components	1.052M / 1,052,099	1.105M / 1,104,704
Total Initial Cost	6.313M / 6,312,596	6.365M / 6,365,201
Initial Cost at Government Subsidy of 50%	3.156M / 3,156,298	3.183M / 3,182,601
Monthly Operational Cost		
Gas Fuel Cost	271,400	271,400
Electrical Cost for Absorption Chiller	453	453
Maintenance	315,600	315,600
Total Monthly Operational Cost	59,160	59,420
Monthly Operational Savings		
Electrical Savings by SOFC Power Generation	76,570	76,570
Electrical Savings on Cooling by Absorption Cooling	8,415	8,415
Fuel Savings on Hot Water Production	N/A	20,640
Total Monthly Operational Savings	84,990	105,600
Payback Period in Months	122.2	68.9
Payback Period in Years	10.2	5.7

Table 2 Summary of Single Factor Sensitivity Analyses for Trigeneration System

	+10% Factor Change		-10% Factor Change	
	Payback Period (Years)	Changes	Payback Period (Years)	Changes
Level of Government Subsidy	4.55	-20.00%	6.82	+20.00%
Rate of Electricity	4.81	-15.42%	6.95	+22.29%
Cost of SOFC Energy Server	6.66	+17.13%	4.83	-15.04%
Cost of Auxiliary Components	6.52	+14.73%	4.94	-13.16%
Cost of Maintenance	6.10	+7.32%	5.32	-6.39%
Rate of Gas Fuel	5.77	+1.42%	5.61	-1.38%
Cost of Absorption Chiller	5.73	+0.81%	5.64	-0.80%

Table 3 Results of Optimistic and Pessimistic Analysis for Trigeneration System

	Optimistic Analysis	**Pessimistic Analysis**
System Cost	Amount (US$)	Amount (US$)
SOFC Energy Server	4.5M / 4,500,000	5.5M / 5,500,000
Absorption Chiller	0.23M /234,447	0.29M / 286,547
Auxiliary Components	0.52M /520,789	1.79M / 1,793,829
Total Initial Cost	5.26M / 5,255,237	7.58M / 7,580,376
Initial Cost at with Government Subsidy	2.10M / 2,102,095	4.55M / 4,548,226
Monthly Operational Cost		
Gas Fuel Cost	24,430	29,860
Electrical Cost for Absorption Chiller	498	408
Maintenance	23,650	41,690
Total Monthly Operational Cost	48,570	71,960
Monthly Operational Savings		
Electrical Savings by SOFC Power Generation	84,230	68,910
Electrical Savings by Absorption Cooling	9,256	7,573
Fuel Savings on Hot Water Production	18,570	22,700
Total Monthly Operational Savings	112,100	99,190
Payback Period in Months	33.11	167.03
Payback Period in Years	2.76	13.92

Changes in Payback Period	-51.93%	142.47%

Table 4 Cogeneration and Trigeneration System Inputs and Outputs

	Fuel Input (kW)	Electricity Input (kW)	Electricity Output (kW)	Cooling Output (kW)	Water Heating Output (kW)	Overall System Efficiency (%)
Cogeneration	1936	4.3	1000	630	N/A	84.02%
Trigeneration	1936	4.3	1000	630	191	93.86%

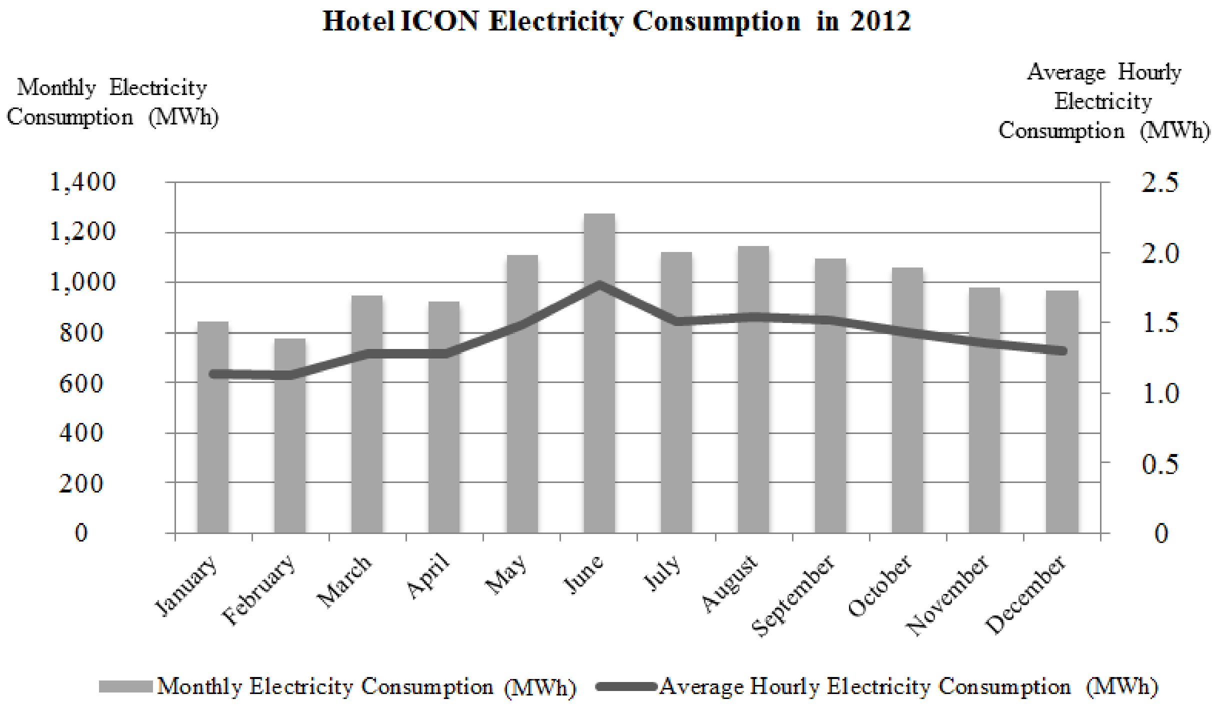

Hotel ICON Electricity Consumption in 2012
Monthly Electricity Consumption (MWh)
Average Hourly Electricity Consumption (MWh)
1,400
1,200
1,000
800
600
400
200
0
2.5
2.0
1.5
1.0
0.5
0
January
February
March
April
May
June
July
August
September
October
November
December
Monthly Electricity Consumption (MWh)
Average Hourly Electricity Consumption (MWh)

Figure 1

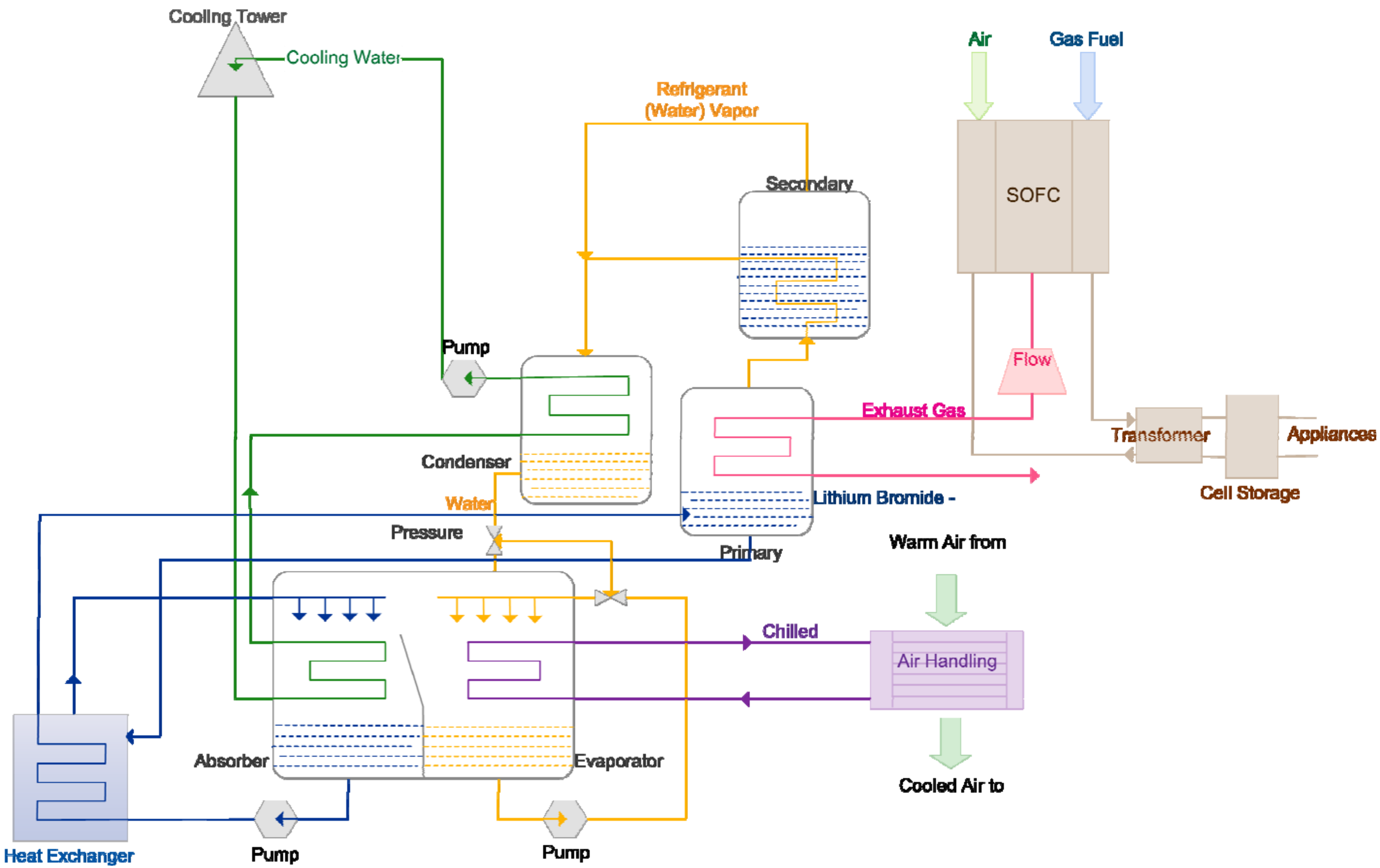
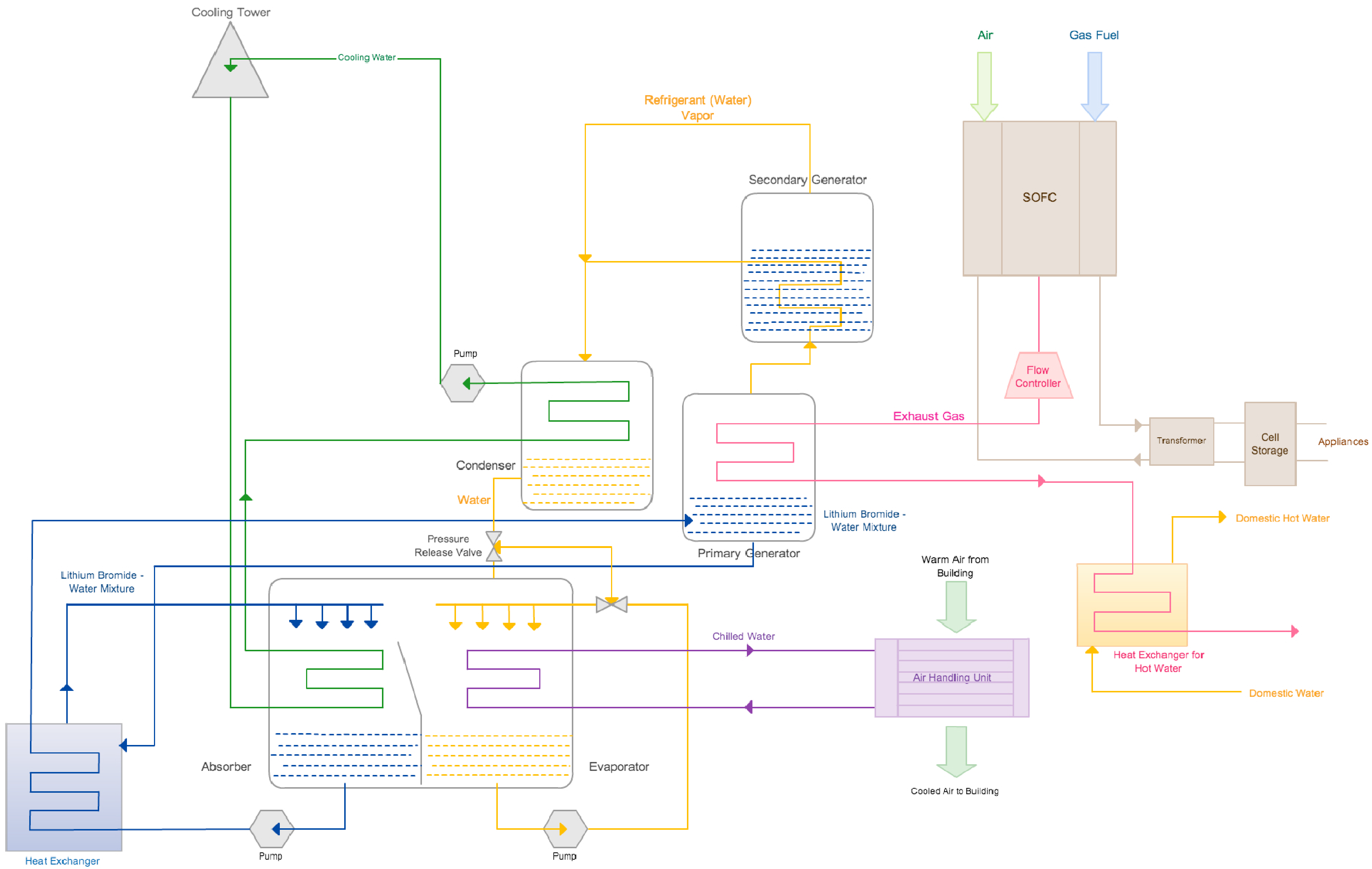


Figure 2 SOFC-Absorption Cooling Building Cogeneration System Configuration



Cooling Tower
Cooling Water
Refrigerant (Water)
Vapor
Air
Gas Fuel
SOFC
Secondary Generator
Pump
Flow
Controller
Exhaust Gas
Transformer
Cell
Storage
Appliances
Condenser
Water
Lithium Bromide -
Water Mixture
Primary Generator
Pressure
Release Valve
Domestic Hot Water
Lithium Bromide -
Water Mixture
Warm Air from
Building
Chilled Water
Air Handling Unit
Heat Exchanger for
Hot Water
Domestic Water
Absorber
Evaporator
Cooled Air to Building
Heat Exchanger
Pump
Pump

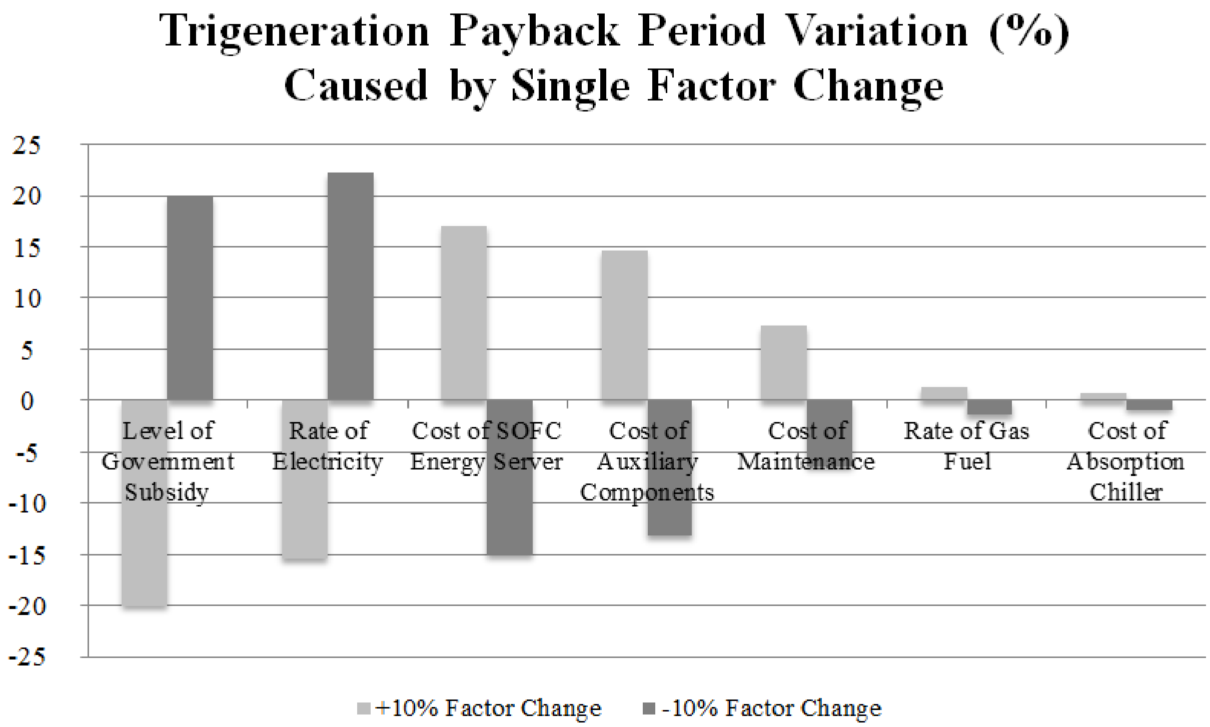

Trigeneration Payback Period Variation (%)
Caused by Single Factor Change
25
20
15
10
5
0
-5
-10
-15
-20
-25
Level of Government Subsidy
Rate of Electricity
Cost of SOFC Energy Server
Cost of Auxiliary Components
Cost of Maintenance
Rate of Gas Fuel
Cost of Absorption Chiller
+10% Factor Change
-10% Factor Change

Figure 4