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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.

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 °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,

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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 ($\eta_{(\mathrm{electricity})}$) and overall efficiency ($\eta_{(\mathrm{overall})}$):

$$\eta_{(\mathrm{electricity})} = \frac{P_{(\mathrm{electrical})}}{\mathrm{FI}} \tag{1}$$

$$\eta_{(\mathrm{overall})} = \frac{[P_{(\mathrm{electrical})} + P_{(\mathrm{thermal})}]}{\mathrm{FI}} \tag{2}$$

where $P_{(\mathrm{electrical})}$ and $P_{(\mathrm{thermal})}$ 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:

$$\eta_{(\mathrm{overall})} = \frac{[P_{(\mathrm{electrical})} + P_{(\mathrm{thermal})} + P_{(\mathrm{hot\,water})}]}{\mathrm{FI}} \tag{3}$$

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 4–38 °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.