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Published in:
Applied Energy

Published: 01/02/2014

Document Version:
Post-print, also known as Accepted Author Manuscript, Peer-reviewed or Author Final version

Published version (DOI):
10.1016/j.apenergy.2013.10.001

Publication details:
Fong, K. F., & Lee, C. K. (2014). Investigation on zero grid-electricity design strategies of solid oxide fuel cell trigeneration system for high-rise building in hot and humid climate. *Applied Energy*, *114*, 426-433. https://doi.org/10.1016/j.apenergy.2013.10.001

Investigation on zero grid-electricity design strategies of solid oxide fuel cell trigeneration system for high-rise building in hot and humid climate

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http://dx.doi.org/10.1016/j.apenergy.2013.10.001

Abstract

Trigeneration, which is able to provide cooling, heating and power, has been advocated to be a sustainable solution for building use in the urban area. With the high-temperature feature and maintenance convenience, solid oxide fuel cell (SOFC) becomes a promising prime mover of trigeneration. In this study, two zero grid-electricity design strategies of SOFC-trigeneration system for high-rise building were proposed and evaluated. The first zero design approach, named full-SOFC strategy, is to design the rated capacity of SOFC by matching the demand peak of electrical power without the need of grid connection. The second one, called partial-SOFC strategy, is to satisfy the peak electrical demand partly by the SOFC and partly by the grid, but still maintaining net zero grid-electricity in a year time. In view of the system complexity and the component interaction of SOFC-trigeneration, the environmental and energy performances of different cases were evaluated through year-round dynamic simulation. Compared to the conventional provisions of cooling, heating and power for building, the full- and the partial-SOFC-trigeneration systems could have 51.4% and 23.9% carbon emission cut per annum respectively. In terms of year-round electricity demand, the two zero grid-electricity strategies had corresponding savings of 7.1% and 2.8%. As a whole, the full-SOFC-trigeneration assures both environmental and energy merits for high-rise building in the hot and humid climate.

Keywords: Trigeneration; Combined cooling, heating and power; Solid oxide fuel cell; Zero grid-electricity; Sustainable cooling and heating.

1. Introduction

The efficiencies of classical power plants usually do not exceed 40%. To improve the situation, distributed power supply systems through cogeneration or even trigeneration can be employed in which the overall system efficiency can be in the range of 60% to 80% [1], depending on the type of prime mover and the temperature level of the heating requirement. Through such approach, the carbon emission can be greatly reduced. In trigeneration, the conventional prime mover is related to the thermodynamic cycle, such as internal combustion engine (ICE), gas turbine or steam turbine. Coupled with the generator set, these cycles are commonly used in electricity generation. In recent years, new thermodynamic cycles have been evolved, like Stirling engine (external combustion engine), mircoturbine and organic Rankine cycle [2]. As emerging technology, fuel cells are also possible to be the prime mover of trigeneration, as waste heat can be captured and utilized. The common types of fuel cells include proton exchange membrane fuel cells, alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells (MCFC) and SOFC. Both MCFC and SOFC are classified as high temperature fuel cells, since their operating temperature is over 600°C.

For trigeneration, the latest technologies, benefits and characteristics, technical performances, utilization and development, linkage with renewable resources have been reviewed and consolidated [1,2]. It is found that the SOFC-driven trigeneration is worth being committed in further studies [3,4]. Comparison of trigeneration system using the prime movers of ICE, gas turbine, Stirling engine and SOFC were carried out for building application [5,6], and particular attention was paid on the criteria of technology and environmental impact. The SOFC is one of the potential choices for the prime mover due to its high efficiency in the electricity generation. Moreover, the high temperature flue gas can be used to provide hot water to drive an absorption chiller for space cooling and hot water for drinking simultaneously. In long-term, SOFC are considered as a more promising technology in fuel cells [7], since they are based on solid electrolyte without expensive catalysts. As their operating temperature is high and internal reforming is possible, a number of fuel types can be applied for hydrogen generation.

In building applications, Weber et al. [8] proposed a decentralized energy system using SOFC with double-effect absorption heat pump for office building. Through numerical simulation, the carbon reduction of the system could be over 30% against the conventional system. Zink et al. [9] conducted simulation study of an internal reforming tubular SOFC coupled with a single-stage absorption heat pump (HP) to generate electricity and cooling/heating for building. The overall efficiency of the SOFC-HP system was 87% for electricity and heating cogeneration, while 95.7% for electricity and cooling cogeneration. Malico et al. [10] designed a demonstration project of SOFC-driven trigeneration based on the electrical load for the hospital application. The trigeneration contained tubular SOFC, absorption chiller and gas boiler, which was added in order to supplement the thermal load of the hospital. Velumani et al. [11] modelled a trigeneration system including SOFC, microturbine and single-effect absorption chiller for distributed generation. A simulation model of the trigeneration system was developed and its performance was evaluated.

These previous studies of SOFC-driven trigeneration were mainly based on steady-state system simulation at the design conditions. However in the building applications, dynamic simulation is necessary in order to fully appraise the system performances with respect to changing building loads and climatic conditions. It is also essential to evaluate the components hence the system characteristics in different operating conditions. On the other hand, although trigeneration is well known to have good overall efficiency, the thermal efficiency would be over-estimated since it is not constant at the rated value. In fact, the thermal efficiency heavily depends on the quality of heat able to be extracted from the flue gas in different loading conditions. It would be more effective to evaluate the system performance based on the solid information, such as the manufacturer's data. Another question is how to realize the trigeneration technology for low carbon building design, especially the provision of cooling for those buildings in the hot-humid climate. And the design approach would be determinable to the capacity sizing of SOFC in the trigeneration system. Therefore, this study is to explore the system performances of SOFC-trigeneration in connection to sustainable strategies through year-round dynamic simulation.

The rest of this paper is organized as follows: Section 2 describes the system design of SOFC-trigeneration, covering the various component equipment for building cooling, heating and power. Section 3 states the design information of the trigeneration system and the building zone in this study, particularly the SOFC component model. Section 4 brings out the methodology of analysis for the two proposed zero grid-electricity design approaches – the full-SOFC strategy and the part-SOFC strategy. Section 5 discusses the results of the year-round system performances, the monthly variation of different performances and the effect on SOFC staging. Section 6 is the conclusion and recommendation.

2. System design of SOFC-trigeneration

Fig. 1 shows the schematic design of the SOFC-trigeneration system serving a multi-storey office building. The fuel reacts electrochemically with the air in the SOFC to generate electricity for the building zone. The unreacted fuel is burnt in the combustor and the hot exhaust flue gas is used to pre-heat the fuel and the air before passing to a hot water generator in which hot water is delivered. This hot water is used to drive the absorption chiller first. A hot water recuperator is placed downstream of the absorption chiller to provide hot water supply for the building zone. In the office building under hot and humid climate, the hot water is mainly used for drinking purpose. An auxiliary heater is installed in the hot potable water stream to supplement the hot water recuperator in order that the temperature of the hot drinking water can be maintained.

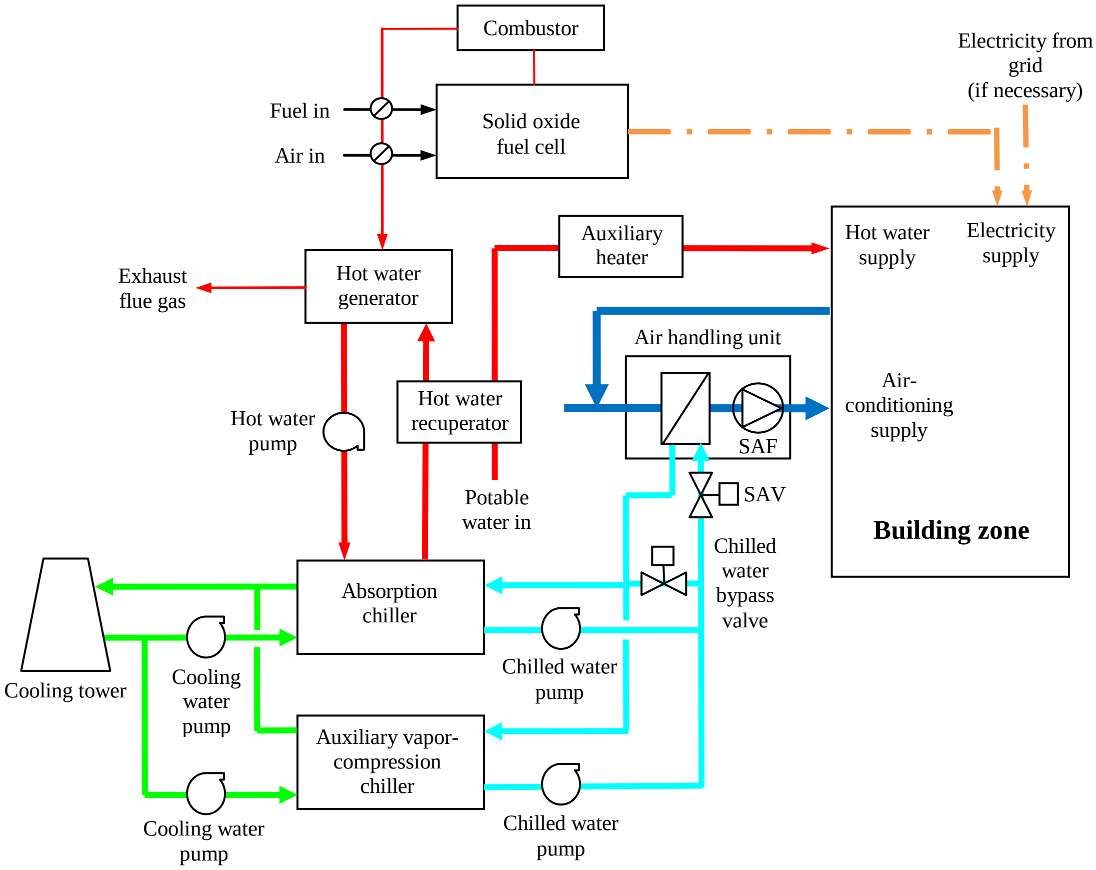

Fig. 1. Schematic diagram of SOFC-trigeneration system.

For the office building in the hot and humid city, the cooling demand is very high. Hence, the waste heat from the SOFC may not be sufficient to provide the necessary cooling requirement. In view of this, auxiliary vapor-compression chillers are involved when the cooling demand is high. Through the chilled water pumps, chilled water is provided to the cooling coil of the air handling unit, then conditioned air is delivered to the building zone by the supply air fan (SAF). As a two-way supply air valve (SAV) is used in each air handling unit, the secondary chilled water flow rate can be varying depending on the operating conditions. A chilled water bypass valve is employed so that the primary chilled water flow rate can be maintained constant. Cooling water pumps are used to remove the heat from chillers to cooling tower for heat rejection purpose. Consequently, a centralized SOFC-trigeneration system is designed for electricity supply, air-conditioning supply and hot water supply for the entire building.

In the proposed SOFC-trigeneration system, the design capacities of SOFC and chillers would be determined in a way that they are enough to satisfy both the electrical and thermal demands at any instant throughout a year. As a result, energy storage is not involved in the system design. In real application, energy storage can also be omitted since the grid connection can provide emergency power supply when necessary.

3. Details of system and building design under study

3.1 Building information

In this study, the SOFC-trigeneration system was designed to serve a 28-storey office building in the subtropical Hong Kong located at 22.32°N and 114.17°E. Each storey had conditioned floor area of 200 m^2 and the zone functional behavior on each floor was the same. The design indoor conditions were 25.5^{o}C and 60%RH. The outdoor air flow rate was 10 litres/s/person. The wall-fenestration ratio was 0.5. The internal and external shading factors of fenestration were 0.8 and 0.2 respectively. The internal heat gains included 24 persons seated at work, 230 W/person of personal computer set, and 17 W/m^2 of lighting with 30% convective part. The provisions and schedules of the internal heat gains were based on the local design practice [12]. Different schedules were adopted for weekdays and weekend as shown in Figs. 2 and 3. For the heating supply, the demand for hot drinking water was scheduled at 9:00 am, 11:00 am, 1:00 pm and 3:00 pm. The office building was assumed to be closed on Sunday.

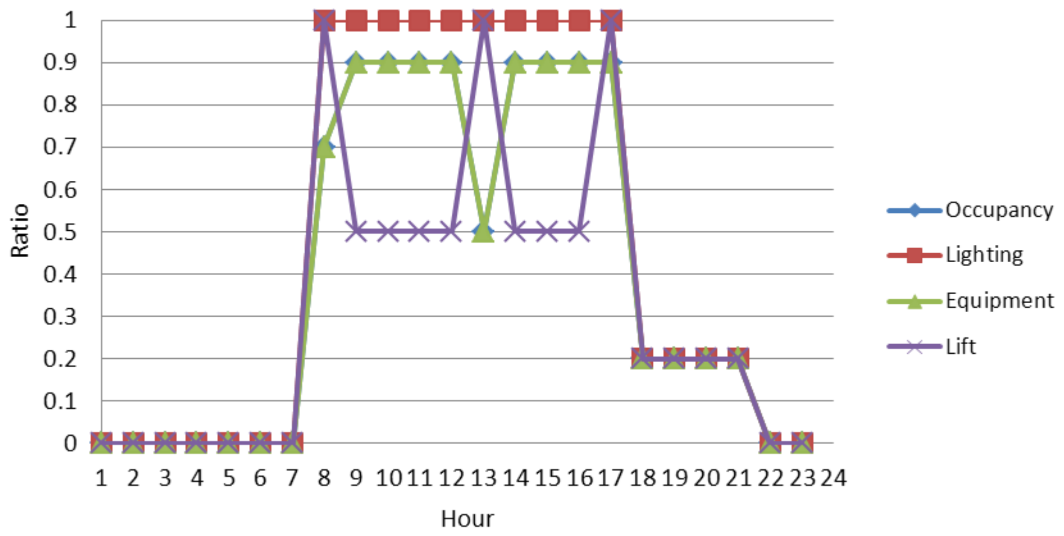

Fig. 2. Schedules for various loadings at weekdays.

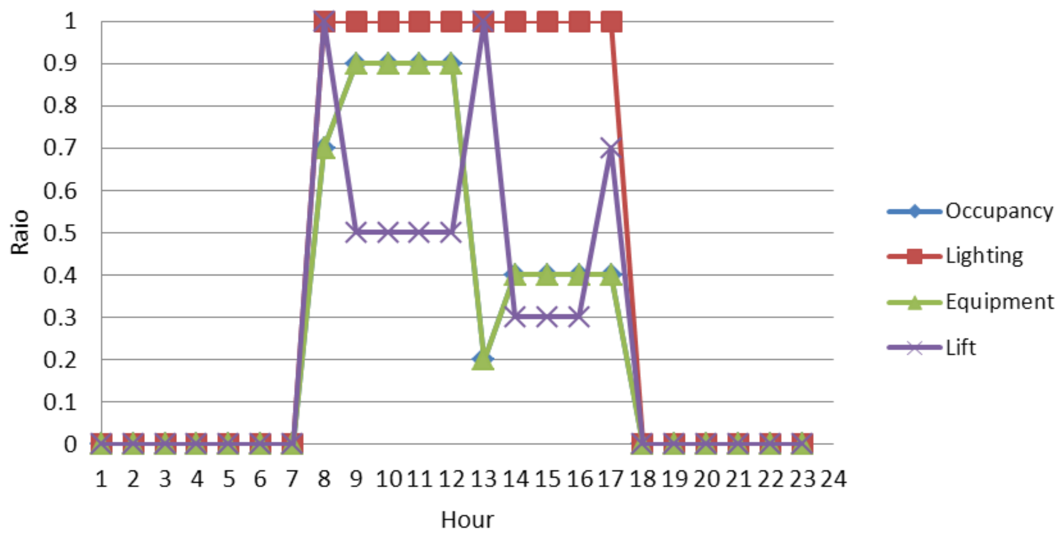

Fig. 3. Schedules for various loadings at weekend.

The electrical demand of the lifts was taken as 40 kVA/lift based on the local code of practice [13] and a power factor of 0.85. Two lifts were used in the building according to the occupant population. The hot drinking water demand was 0.2 litre per occupant with a temperature of 95°C. The temperature of the entering potable water was assumed to rise linearly from 15°C in January to 25°C in July and then drops back linearly.

3.2 *SOFC modelling*

In this trigeneration system, the SOFC component model was built according to the manufacturer's information [14]. The fuel employed by the SOFC was natural gas. The SOFC operated under the rated conditions with a design electricity generation efficiency of 47%. The available waste heat from the SOFC depended on the hot water supply temperature ($T_{hw,s}$). In this case, a parameter of SOFC performance called waste heat utilization factor (*WHUF*) was introduced. *WHUF* is defined as the proportion of waste heat that can be recovered from the exhaust flue gases of SOFC for heat-driven purpose. A parabolic correlation was found between *WHUF* and $T_{hw,s}$ from the information of three SOFC models of products (DFC300, DFC1500 and DFC3000) of [14], as shown in Fig. 4. The curves for the three models can be treated identical.

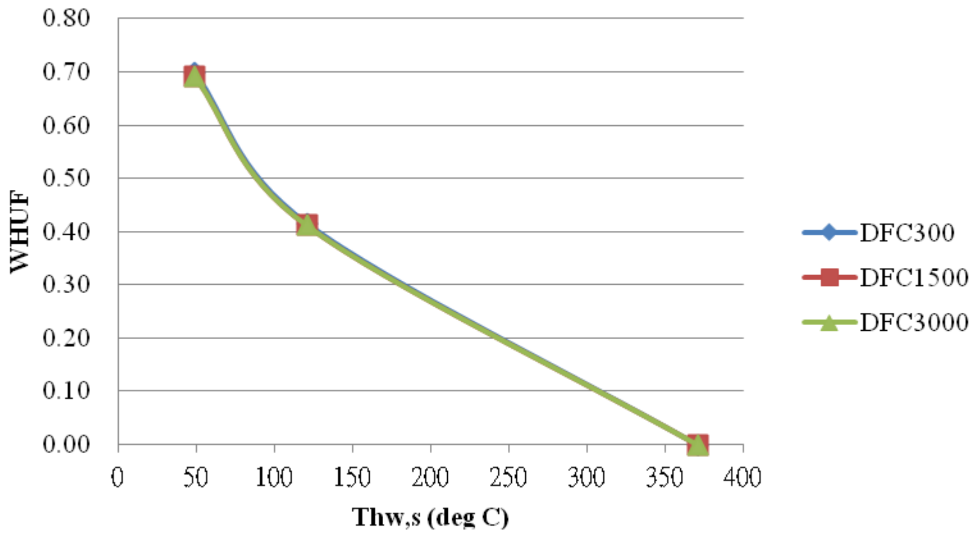

Fig. 4. Variation of *WHUF* with $T_{hw,s}$ for various SOFC models.

The empirical coefficients for the SOFC model are adopted as shown below:

$$WHUF = 7.04802 \times 10^{-6} T_{hw,s}^2 - 0.00513 T_{hw,s} + 0.934115 \quad (1)$$

The sizing of the SOFC capacity was based on the electrical demands in the building and the strategies to be adopted to avoid the grid-electricity. The electricity demands in the office building mainly came from the lighting, electrical office appliances, the lifts and other building services facilities like the auxiliary vapor-compression chiller, cooling tower and water pumps in the chiller plant, as well as the supply air fans of the air handling units.

3.3 Details of other component equipment of trigeneration system

According to the previous study about the various thermally-driven cooling systems [15], the single-effect absorption chiller offers the best year-round energy performance in hot and humid climate. In principle, a higher coefficient of performance (*COP*) can be achieved if a double-effect absorption chiller is employed, with the hot water supply temperature of up to 175°C. However, according to the SOFC performance shown in Fig. 4, the provision of a higher hot water supply temperature reduces the *WHUF* substantially. The overall system result would not be beneficial. As a result, only single-effect absorption chiller was considered in this trigeneration system design.

In view of the ratio of the air-conditioning demand to the total electricity demand during the peak-load season, one absorption chiller and two vapor-compression chillers were used. Each chiller was equipped with individual cooling water and chilled water pumps. The design *COP's* for the absorption chiller and the vapor-compression chiller were 0.75 [16] and 4.6 [17] respectively based on the entering hot water, cooling water and chilled water temperatures of 110°C, 30°C and 13°C where applicable. The water flow rates for the cooling water and chilled water pumps were selected so that there was a temperature change of 5°C across the chiller. Meanwhile, the design temperature drop for the hot water across the absorption chiller was 10°C. The fuel employed by the auxiliary water heater was also natural gas, and the energy efficiency of the auxiliary water heater was taken as 90%. Table 1 summarizes the other parameter values used in this study of SOFC-trigeneration system.

Table 1. Other parameter values used for the trigeneration system.

Design parameter	Value
Total cooling demand (kW)	814
Peak total electricity demand besides air-conditioning system (kW)	375
Total heating demand for the hot drinking water (kW)	15
Supply air flow for each air handling unit (kg s^{-1})	2.15
Supply fan head (Pa)	750
Supply fan efficiency	75%
Face area of cooling coil for each air handling unit (m^2)	0.9
Cooling tower fan head (Pa)	200
Cooling tower fan efficiency	65%
Cooling water pump efficiency	50%
Chilled water pump efficiency	50%
Hot water pump efficiency	50%
Overall heat transfer coefficient of hot water recuperator (kW K^{-1})	0.444

3.4 Control and operation

The sequencing of the vapor-compression chillers was governed by the respective average part-load ratio. With the return chilled water temperature exceeding 13°C, the absorption chiller was energized. If the return chilled water temperature was still higher than 13°C after one simulation time step, the first vapor-compression chiller was switched on. When the part-load ratio of the first vapor-compression chiller exceeded 0.999, the second vapor-compression chiller was called. In case the average part-load ratio of the vapor-compression chiller fell below 0.5 and that the chilled water return temperature was under 13°C, one vapor-compression chiller would be stopped. The remaining vapor-compression chiller was de-energized if its part-load ratio dropped below 0.2. The absorption chiller was switched off when the return chilled water temperature fell below 10°C. The functioning of the chilled water pumps followed that for the respective chillers, except that for the absorption chiller which was continuously operated within the entire daily schedule. The cooling water pump was energized when the chiller was started, and the cooling tower was additionally controlled according to the cooling water temperature leaving the chiller by a thermostat with hysteresis between 15 and 20°C.

For the air-handling unit, the SAV was controlled by a proportional controller within ±1°C of the zone temperature set point. The SAF was operated continuously during the entire daily schedule. The hot water pump was energized whenever the absorption chiller was operated or when hot drinking water was required.

4. Methodology of analysis

4.1 Proposed zero grid-electricity design strategies

As mentioned in Section 1, the strategies of sustainable design would be associated with the capacity sizing of SOFC in the trigeneration system. In this study, two zero grid-electricity approaches were proposed:

- the full-SOFC strategy (without grid connection); and
- the partial-SOFC strategy (with grid connection).

In the full-SOFC strategy, it was assumed that the building was sufficient in electricity supply even without grid connection. Hence, the design capacity of the SOFC must be capable of providing the necessary electricity and heat during the peak-load season. The SOFC would be operated within the daily schedule during weekdays and weekend. To reduce the fuel consumption and hence the CO_2 emission, the SOFC was assumed to be composed of a number of identical stages. The SOFC clusters were equally divided into groups according to the number of stages for staging purpose. In staging operation, each group of SOFC was switched in or out according to the loading demand. The number of stages selected was based on the criteria that the electricity output from one stage was sufficient to serve the minimum demand throughout the year. Eq. (1) for *WHUF* was still applicable when the number of stages was changed. The number of operating stages depended on the actual electricity demand in such a way that the total electricity output from the SOFC must be sufficient to fulfill the electricity requirement at anytime. In this sense, a surplus electricity supply from the SOFC could be expected. The hot water flow rate to each stage was maintained constant when the SOFC was functioning. Hence, the total hot water flow rate to the absorption chiller varied with the number of operating stages for the SOFC. As the capacity of the absorption usually changed to a lesser extent as compared to the hot water supply flow rate, the hot water temperature would drop more at a lower hot water supply flow rate. This in turn affected *WHUF*, and the entering hot water temperature would decrease until the available waste heat from the SOFC matched the demand. In this circumstance, the auxiliary heater for the potable water might need to be called in.

In the partial-SOFC strategy, the second approach, it was assumed that the building was connected to the electricity grid. Hence, auxiliary electricity could be supplied from the grid during the peak-load season. Conversely, surplus electricity from SOFC could also be fed to the grid during the low-load periods so that the net electricity transfer through the grid was zero in a year time. To further reduce the capacity of the SOFC, the SOFC was assumed to be operated continuously throughout the year at full capacity. As the available waste heat and hence the capacity of the respective types of chillers as well as the energy demands from the parasitic equipment depended on the capacity of the SOFC, repeated trial-and-error was used to determine the equipment capacities in this zero grid-electricity design strategy. As the capacity of the absorption chiller also depended on the respective cooling and chilled water entering temperatures, the amount of heat consumed by the absorption chiller would vary from time to time. Consequently, $T_{hw,s}$ still fluctuated even though the hot water flow rate remained constant throughout the time.

In both strategies, the maximum available waste heat from SOFC was calculated using Eq. (1) under the design hot water supply temperature of 110°C when the capacity of the SOFC was set. The design capacity of the absorption chiller was then determined from the rated *COP*. Consequently, the required total capacity for the auxiliary vapor-compression chillers could be worked out.

4.2 Dynamic simulation and performance parameters

Dynamic system simulations were conducted in a simulation time step of six minutes for one year by using TRNSYS [18] and its component library TESS [19]. The year-round typical meteorological data of Hong Kong [20] was adopted. Standard TRNSYS component models were available for all the major equipment, including water-cooled vapor-compression chiller (Type666), cooling tower (Type51), water pumps and fans (Type3), cooling coil (Type52), hot water recuperator (Type5) and building zone (Type56). For the single-effect absorption chiller, a parametric model previously outlined in [21] was employed. Unless otherwise specified in Section 3, default parameters of the TRNSYS component models were used.

The overall efficiency of SOFC for trigeneration (η_o) was calculated as follows:

$$\eta_o = \eta_e + (1 - \eta_e)WHUF \tag{2}$$

Here, η_e is the electricity generation efficiency of SOFC. From Eq (2), the overall efficiency of SOFC for trigeneration depends on both η_e and *WHUF*. The former is steady at the rated value of 47% in operation, while the latter is associated with the changing hot water supply temperature as described in Eq (1).

The energy consumption and CO_2 emission for the two strategies would be compared with the conventional system, in which the electricity from grid was the sole energy source. In the conventional system, air-conditioning was fully served by two sets of electric vapor-compression chillers, and electric water heater was used to provide the hot drinking water. In evaluating the CO_2 emission from the various energy sources, the local guidelines of Building Environmental Assessment Method [22] was adopted. For the electricity from the local grid, the equivalent carbon emission is 0.7 kg CO_2 per kWh_e. For the natural gas fed to SOFC, the equivalent carbon emission is 0.3659 kg CO_2 per kWh_e, as determined by the carbon emission of natural gas (2.31 kg CO_2 per kg gas) and the gas consumption of SOFC (0.1584 kg gas per kWh_e from [14]). For the natural gas fed to the water heater, the equivalent carbon emission is 0.1663 kg CO_2 per kWh_t.

5. Results and discussions

5.1 Capacities of SOFC and chillers

Based on the two zero grid-electricity strategies for designing the SOFC-trigeneration, the capacities of SOFC and absorption chiller were determined and summarized in Table 2. The remaining cooling load was handled by the vapor-compression chillers. Here, the SOFC was composed of four stages according to the idea stated in Section 4.1 for the full-SOFC-trigeneration without grid connection. From Table 2, the required capacity of the SOFC of the partial-SOFC-trigeneration was 31.5% of that of full-SOFC-trigeneration. The absorption chiller capacity would also have a similar ratio at 31.6%. However, this means that the possible electricity saving in air-conditioning would be less in the partial-SOFC-trigeneration, since more involvement of vapor-compression chillers would be expected.

Table 2. Capacities of SOFC and chillers in the two zero grid-electricity design strategies.

Case	SOFC capacity (kW)	Capacity of absorption chiller (kW)	Total capacity of compression chillers (kW)
Full-SOFC-trigeneration (without grid connection)	593	228	293 × 2
Partial-SOFC-trigeneration (with grid connection)	187	72	371 × 2

5.2 Year-round performances

Table 3 summarizes the year-round simulation results for the various cases under investigation. About the year-round electricity demand, the saving could be 7.1% for the full-SOFC-trigeneration system as compared to the conventional system. On the other hand, the electricity demand from the partial-SOFC-trigeneration system was only saved by around 2.8%. The electricity reduction of the two trigeneration systems was mainly because the heat-driven absorption chiller had handled part of cooling load. Natural gas was required for auxiliary heating in both full- and partial-SOFC-trigeneration systems, however the demands were not significant compared to the electricity demand from the energy perspective. About the total consumption of natural gas, the full- and partial-SOFC-trigeneration systems were comparable, even the former could be 4.2% less than the latter.

Table 3. Comparison of the year-round performances for the various cases.

Case	Electricity demand (MWh)	Gas demand for auxiliary heating (MWh)	Total gas consumed (Ton)	Total carbon emission (Ton)	Yearly-averaged η_o
Conventional system	1,685	NA	NA	1,180	NA
Full-SOFC-trigeneration (without grid connection)	1,566	5.3	248	574	75.2%
Partial-SOFC-trigeneration (with grid connection)	1,638 (745 from SOFC; 893 from grid)	4.5	259	898 (273 due to consumed gas; 625 due to grid electricity)	71.0%

Remark: "NA" means "not applicable".

The reduction in the CO_2 emission was more pronounced with the use of the full-SOFC-trigeneration, which was primarily due to the choice of fuels. As mentioned in Section 4.2, the carbon emission of the grid electricity is about double of that of the natural gas for SOFC according to the local fuel mix of electricity generation. This explains why the corresponding savings in the CO_2 emission, which measured 51.4% and 23.9% respectively when the trigeneration systems were operated in full-SOFC and partial-SOFC strategies, would differ so much. Even the net electricity transfer through the grid was maintained at nearly zero for the partial-SOFC-trigeneration, the CO_2 emission was not balanced. The electricity from the grid accounted for 54.5% of the year-round demand, but its carbon emission would be going up to 69.6% of the annual total.

From Table 3, the overall efficiency of both trigeneration systems could be above 70%, demonstrating the system effectiveness by using SOFC with high electrical generation efficiency. Besides the merit of carbon emission cut, the full-SOFC-trigeneration could have better yearly average overall efficiency than the partial-SOFC-trigeneration.

5.3 Monthly variation of different system performances

Besides the year-round analysis, it can provide more insights about the system performances throughout different months in a year. Therefore, the electricity demand, gas consumed, carbon emission and overall efficiency of the various systems were evaluated in the monthly basis and discussed in the following sub-sections.

5.3.1 Electricity demand

The profiles of monthly variation of electricity demand are illustrated in Fig. 5. No matter the conventional system or the trigeneration systems, the profiles had the peak in August and the trough in February. This reflects that the total electricity demand mainly followed the building cooling load around the year in a subtropical region, since the electricity demands (like lighting, office appliances and lifts) other than air-conditioning were fairly constant. Similar to the finding in Table 3, the full-SOFC-trigeneration had the lowest profile of electricity demand, while the conventional system had the highest. However the difference of electricity demand was insignificant during the low season between December to March.

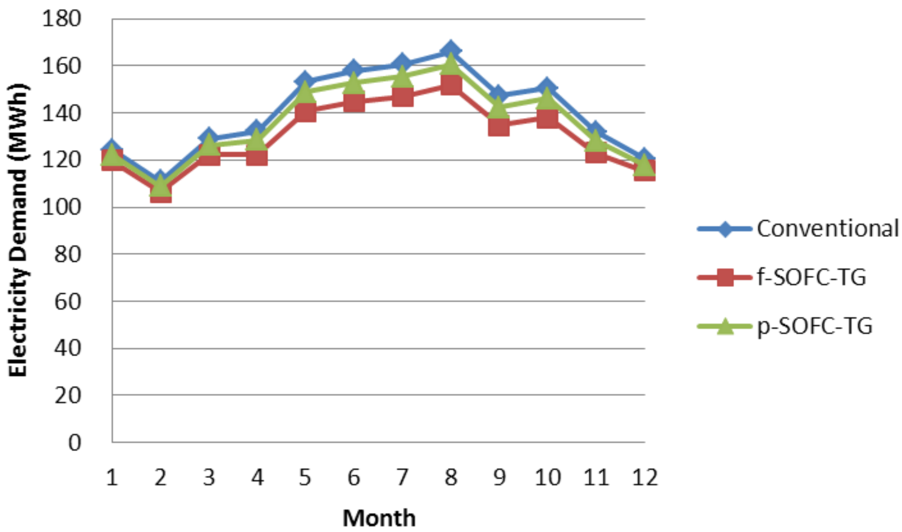

Fig. 5. Monthly variation of electricity demand of different systems.

5.3.2 Consumption of natural gas

From Table 3, the amounts of gas consumed by two trigeneration systems were close, however the profiles were quite different as found in Fig. 6. The profile of the full-SOFC-trigeneration is similar to that of its electricity demand mentioned before, which was related to the seasonal change of building cooling load. The monthly variation of the partial-SOFC-trigeneration is relatively constant, with a narrow change between 20 and 22 Tons of natural gas consumed only. In this case, the SOFC operated continuously throughout the whole year, so the amount of gas consumption mainly depended on the number of days in a month. Even its SOFC capacity is less than one-third of that of the full-SOFC-trigeneration, their gas consumptions did not differ so much, which is reflected from the two profiles in Fig.6.

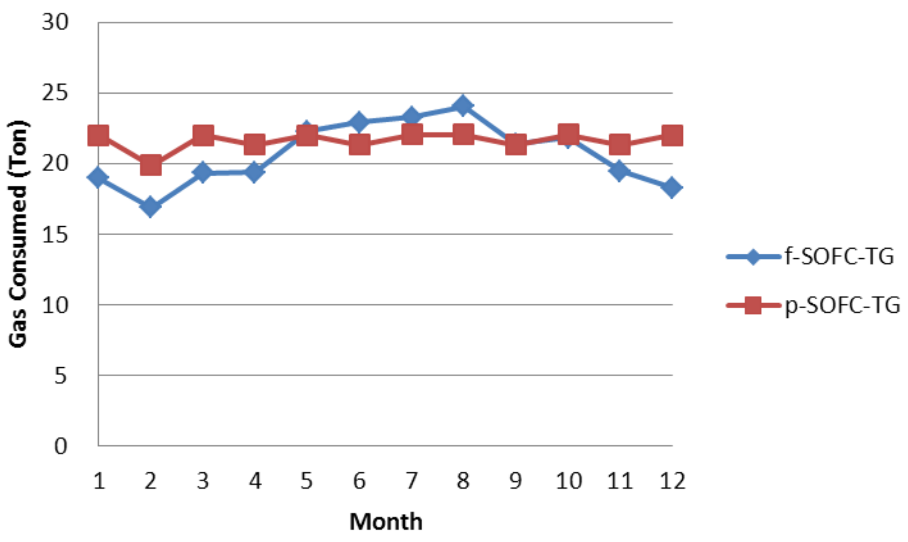

Fig. 6. Monthly variation of natural gas consumption of the two trigeneration systems.

5.3.3 Carbon emission

Fig. 7 contrasts the profiles of carbon emission of different systems involved in this study. Generally the profiles followed the cooling demand of building throughout a year, with the peak in August and the trough in February. Clearly, the carbon emission of the conventional system was the highest, since it fully relied on the grid electricity, which had a higher ratio of carbon emission to electricity generated. The full-SOFC-trigeneration had the lowest profile because the natural gas, which had a lower carbon emission ratio, was the sole fuel input. The profile of the partial-SOFC-trigeneration was in the middle, due to the fact that both the grid electricity and the natural gas were required.

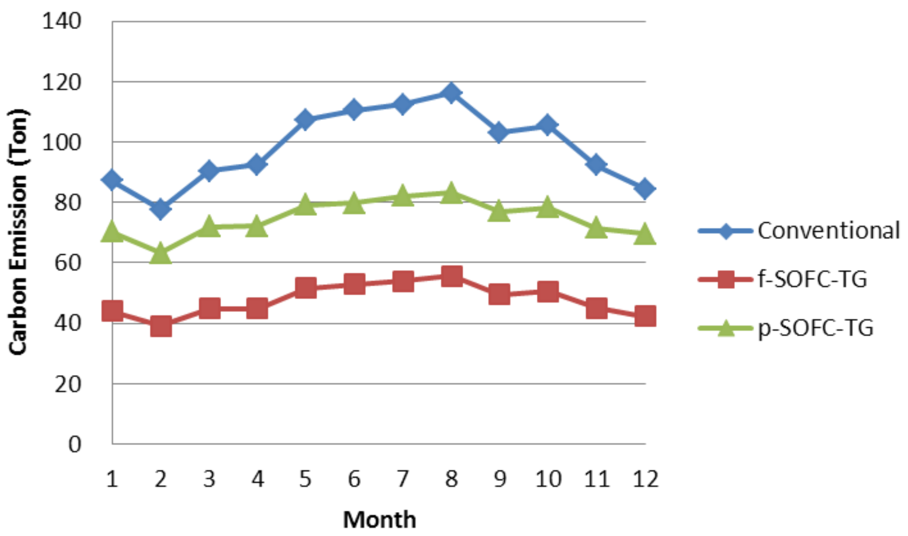

Fig. 7. Monthly variation of carbon emission of different systems.

5.3.4 Overall efficiency of trigeneration system

Fig. 8 depicts the variation of the monthly-averaged overall efficiency for the two trigeneration systems analyzed. The two profiles of η_o are very different, the full-SOFC-trigeneration has the peak around January and the trough around July, while the partial-SOFC-trigeneration is opposite. As recalled from Eq (2), η_o is directly associated with *WHUF* for a constant η_e. In the full-SOFC-trigeneration system, since the average operating stages in the summer period were higher, the hot water flow rate became larger. This resulted in a higher $T_{hw,s}$ and correspondingly a lower *WHUF*, hence lower η_o. The η_o of the full-SOFC-trigeneration system could be up to 76.7% in both December and January, while down to 74.1% in June and August.

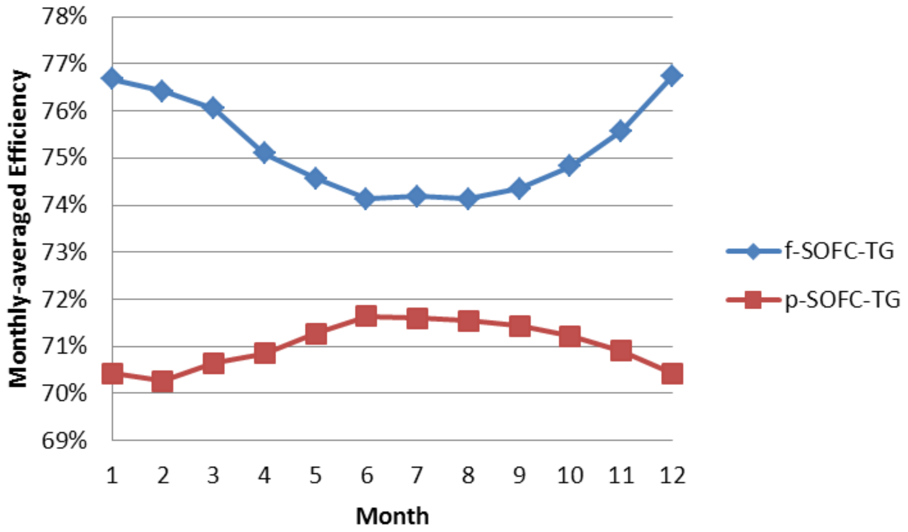

Fig. 8. Variation of the monthly-averaged overall efficiency of the two trigeneration systems.

In the partial-SOFC-trigeneration, as the SOFC was in continuous operation through the year at full capacity, *WHUF* depended primarily on the capacity of the absorption chiller which was in turn governed by the entering cooling water and return chilled water temperatures in the opposite sense. During the low-load season from December to February, both the water temperatures were lower. On the other hand, they were both higher during the peak-load period. The combined effect was therefore complex. Indeed, the operating capacity of absorption chiller fluctuated only mildly throughout the year, since it was used to handle the base load in general. Consequently, *WHUF*, hence η_o, varied to a much lesser extent with time as compared to that of full-SOFC-trigeneration. With the hot water flow rate maintained at the maximum value during the operating schedule, the averaged $T_{hw,s}$ became higher, resulting in a lower *WHUF*. The monthly-averaged η_o of the partial-SOFC-trigeneration is ranged from 70.3% in the cold season to 71.6% in the hot season, all below that of the full-SOFC-trigeneration.

5.4 Effect on SOFC staging in full-SOFC strategy

The values for the total electricity demand and CO_2 emission for the full-SOFC-trigeneration system as indicated in Table 3 only took into account those actually attributed to the operation of the building services systems in the building. As mentioned before, there was a surplus electricity supply from the SOFC in this strategy due to the fact that the number of stages for the SOFC was finite. It would be argued that this surplus electricity supply could be reduced if more stages were broken down for the SOFC aggregate. A parametric study of the effect of stages for SOFC on system performances was therefore conducted. Table 4 shows the respective year-round system performances when the number of stages for the SOFC was increased from four to five and six. It is found that the surplus electricity from the SOFC reduced substantially when more stages were used for the SOFC. However, with a smaller stage capacity, available waste heat from the SOFC also decreased. Consequently, the energy consumption from the vapor-compression chiller (hence the total electricity demand) and the auxiliary heaters both increased accordingly, as indicated in Table 4. Nevertheless, the impact was relatively mild as compared to the reduction in the surplus electricity supply from the SOFC. As a whole, the total consumption of natural gas, hence the total carbon emission, was slightly increased when the number of stages for SOFC was stepped up to 5 or 6. This justifies the use of 4 stages for SOFC in the full-SOFC-trigeneration in this study.

Table 4. Comparison of the year-round performances for the full-SOFC-trigeneration system in different number of stages for the SOFC.

Number of stages for SOFC	Electricity demand (MWh)	Total surplus electricity from SOFC (MWh)	Gas demand for auxiliary heating (MWh)	Total gas consumed (Ton)	Total carbon emission (Ton)
4	1,566	300	5.3	248.0	573.9
5	1,572	270	6.1	249.0	576.4
6	1,573	218	6.1	249.2	576.7

6. Conclusion

In this study, two zero grid-electricity design strategies of SOFC-trigeneration for high-rise building were investigated, including the full-SOFC strategy without grid connection and the partial-SOFC strategy with grid connection. Through the validated model of SOFC and dynamic simulation on the TRNSYS platform, it is found technically feasible to apply either strategy as the trigeneration design. Compared to the conventional system provisions, the full-SOFC-trigeneration could have 51.4% carbon emission cut and 7.1% electricity saving, while the partial-SOFC-trigeneration had 23.9% and 2.8% less respectively. The reduction of electricity use of the trigeneration systems was mainly due to the involvement of the heat-driven absorption chiller. Among the two zero grid-electricity strategies, the full-SOFC-trigeneration was more advantageous than the partial-SOFC-trigeneration in both environmental and energy aspects, since the latter needed to rely on the feed of grid power, which had a higher ratio of carbon emission to electricity generated.

About the performances of the full-SOFC-trigeneration system, it could have the monthly-averaged overall efficiency in the range from 74.1% to 76.7%, which is far higher than the electricity from grid with typically less than 40%. The profiles of electricity demand, gas consumption and carbon emission generally followed the building cooling load in the subtropical climate, with the peak in August and the trough in

February. It can be concluded that the zero grid-electricity strategy of full-SOFC-trigeneration is more suitable for the typical office buildings with the hot and humid climate. Future study will be focused on the involvement of bottoming cycle (such as gas or steam turbine cycle) of SOFC, in which the recovered heat can be further utilized for generating more electricity. Owing to the environmental and energy merits, promotion of effective trigeneration system design would certainly contribute to the sustainable urbanization with continuous economic and population growth.

Acknowledgement

This work described in this paper is fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. CityU 123812).

Nomenclature

COP	Coefficient of performance of chiller
$T_{hw,s}$	Hot water supply temperature from fuel cell (^{o}C)
WHUF	Waste heat utilization factor of fuel cell
η_e	Electricity generation efficiency of fuel cell
η_o	Overall efficiency of SOFC for trigeneration

Abbreviations

HP	Heat pump
ICE	Internal combustion engine
MCFC	Molten carbon fuel cell
SAF	Supply air fan
SAV	Supply air coil valve
SOFC	Solid oxide fuel cell

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