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Environmental and Efficiency Analysis of Simulated Application of the Solid Oxide Fuel Cell Co-Generation System in a Dormitory Building

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Abstract: The problem of air pollution in Korea has become progressively more serious in recent years. Since electricity is advertised as clean energy, some newly developed buildings in Korea are using only electricity for all energy needs. In this research, the annual amount of air pollution attributable to energy under the traditional method in a dormitory building, which is supplying both natural gas and electricity to the building, was compared with the annual amount of air pollution attributable to supplying only electricity. The results showed that the building using only electricity emits much more air pollution than the building using electricity and natural gas together. Under the traditional method of energy supply, a residential solid oxide fuel cell cogeneration system (SOFC–CGS) for minimizing environmental pollution of the building was simulated. Furthermore, as a high load factor could lead to high efficiency of the SOFC–CGS, sharing of the SOFC–CGS by multi-households could increase its efficiency. Finally, the environmental pollution from using one system in one household was compared with that from sharing one system by multi-households. The results showed that the environmental pollution from sharing the system was relatively higher but still similar to that when using one system in one household.

Keywords: environmental impact; device efficiency; air pollutant; multi-households; solid oxide fuel cell cogeneration system

1. Introduction

1.1. Research Background

Electricity as non-combusted energy is advertised to the public as clean energy. Since the price of natural gas and the price of electricity for residential use are similar [1], in the areas of architecture and construction, some real estate developers have been developing new buildings using only electricity for power. However, as a secondary energy resource, electricity is either clean or not clean depending on the electricity generation procedure. In Korea, 39% of electricity is generated from burning coal and only 4% is generated from renewable resources as seen in Figure 1 [2].

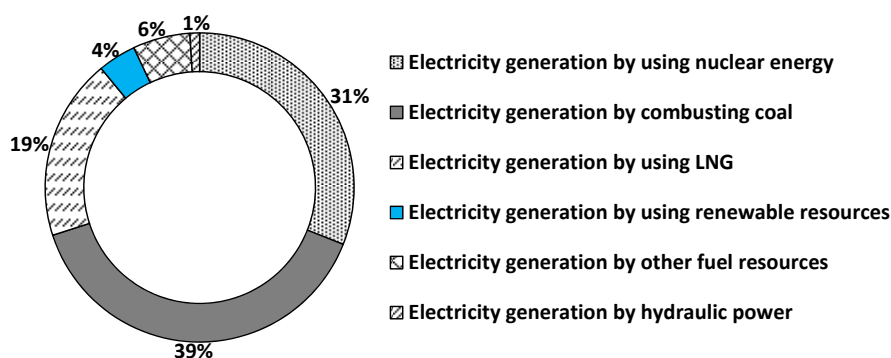


Figure 1. Electricity generation system in Korea.

The traditional method of supplying energy to a building in Korea is mainly using natural gas for heating and hot water and using electricity for lighting, cooling, and equipment. A recent method of supplying energy to a building is using only electricity for all energy needs in the building. This research compared the annual amount of air pollution attributable to energy under the traditional method in a dormitory building, which is supplying both natural gas and electricity to the building and the annual amount of air pollution attributable to supplying only electricity.

A solid oxide fuel cell (SOFC) is a clean energy device for generating electricity by consuming hydrogen or natural gas. By utilizing chemical interaction in the cell stack during the process of electricity generation in SOFC, there is no environmental pollution. However, there is a large amount of heat dissipation during SOFC operation. In order to improve the efficiency of SOFC, the SOFC cogeneration system (SOFC-CGS) was developed to collect and use the heat loss. The heat dissipation generated from SOFC is collected by residential SOFC-CGS and supplied to a hot water tank for hot water demand of a household. A fuel cell as a clean energy system is widely studied for residential use. In recent years, various researches were done about optimizing the operation efficiency of a fuel cell. Some scholars proposed efficiency optimization methods of a fuel cell through improving working principles of electronic components. Wang et al. proposed a novel stack and converter interpreted design scheme to improve the converter efficiency [3]. A micro tri-generation system could increase the system efficiency to over 90% [4]. An energy management system could also achieve cost reduction, CO₂ mitigation, and energy consumption [5]. Some scholars aim to find a way to improve the efficiency of a fuel cell from analysis of energy demand, energy distribution, and energy supplication of a fuel cell. Adam et al. presents a multi-objective modeling approach that allows an optimized design of micro-combined heat and power (CHP) systems considering the source, distribution and emission requirements in unison to achieve more efficient whole systems [6]. Coordination between utilization factor of SOFC and features of a DC/AC (Direct current/Alternating current) inverter is also an efficient control strategy for SOFC operation [7]. Some researchers have combined a photovoltaic, battery, or heat pump with a fuel cell to satisfy the energy needs by a household while reducing cost and CO₂ emission [8–10]. From a wider energy supply perspective, SOFC was considered to supply energy for both households and EV (Electric vehicle) to improve the efficiency and energy supply capacity of SOFC. Using a hydrogen supply system for a residential fuel cell to provide energy for fuel cell vehicles is also a method to solve the problem of lacking hydrogen stations for fuel cell vehicles [11,12]. Field experimental studies demonstrated that a residential fuel cell could significantly reduce the CO₂ emissions and primary energy consumption [13]. Accurate mathematical models were developed to analyze the performance of SOFC. A 1D dynamic model was built for studying system integration and developing adequate energy management and control strategies of SOFC systems [14]. Gallo et al. developed a model of a non-conventional SOFC system by applying a lumped energy balance to each component. This model could efficiently increase the heat exchanges inside the system. This model is verified by experiments and applicable to numerous layouts [15]. According to reference [16], a fuel cell is mainly used in America, Europe, South Korea

and Japan worldwide. From environmental aspect, analysis of CO₂ reduction by a fuel cell was also shown in recent researches from Europe, Japan and South Korea. Fuel cell for EV is mainly applied and investigated in Korea. Environmental impact of CO₂ reduction and emission by fuel cell EV is conducted [17,18]. In order to encourage the utilization residential fuel cell in households in Korea, Lim et al. did a study in the view of CO₂ emissions reduction by applying residential fuel cell [19]. European researchers did several analyses of applying SOFC in the industrial area to reduce CO₂ emission [20,21]. On the other hand, a residential fuel cell is mainly studied in Japan in recent years. The CO₂ emission density of a public power plant was used to calculate the amount of CO₂ emission and CO₂ reduction can be calculated by a simulating application of a fuel cell in a household [22–24]. The same calculation method was used for environmental analysis in this research. From the energy demand oriented research, Ozawa et al. indicates that SOFC–CHP systems can drastically reduce greenhouse gas (GHG) emissions from a particularly small-sized household [24]. Another aspect studied in this research is the efficient operation of SOFC–CGS in small-sized households in a dormitory building by using a exist model of SOFC–CGS from Japan [25–27]. This study analyzed efficiency improvement and environmental impact of operating SOFC–CGS in a dormitory building in Korea by simulating SOFC–CGS operation in multi-households. Under the traditional energy supply method, solid oxide fuel cell cogeneration system (SOFC–CGS) was attempted to simulate applying in the target building of this research. The target building was a dormitory building near a university in Korea. In Korea, the dormitories inside the university campus usually cannot accommodate all of the students registered in the university. Thus, most of the students have to rent a small room for living off campus. Therefore, there are a lot of dormitory buildings near universities in Korea. The dormitory building usually contains several households in each floor and area of one household is around 20 to 30 m², which can only accommodate one or two students. The target building is near a university campus in Busan. Specifications of the target building can be checked in Table 1 in Section 2.1. SOFC–CGS is a clean energy system that does not release any air pollutants when it generates electricity [6,14,24,28]. The device efficiency and environmental impact were analyzed under the conditions of applying one system to one household and applying one system to multi-households to identify the most appropriate way to operate SOFC–CGS in the building. The model of SOFC–CGS is introduced in Section 4. Four different types of energy supply were considered in this research. The first type was supplying only electricity to the building, and the second type was supplying natural gas and electricity together. According to the analysis result, the second energy supply type emits a relative smaller amount of air pollutants than the first type and the efficiency of using natural gas directly by combustion is much higher than using natural gas by SOFC for heating. Therefore, the third type was applying one SOFC–CGS to one household under the second energy supply type, and the fourth type was applying one SOFC–CGS system to multi-households under the second energy supply type.

Table 1. Building specifications.

Parameter	Specific Characteristic
Area	172.3 m ²
Structure	Steel–concrete
Envelop	Concrete
Aboveground Stories	4
Underground Stories	0
Story height	2.6 m
Height	10.4 m
Width	12.6 m
Length	14.5 m
Service life	50 years

1.2. Research Methodology

This study mainly used the commercial software Design Builder (Version 4.5, DesignBuilder Software Ltd, London, UK) to predict energy consumption of the building. In the second part of this research, to simulate operating the SOFC–CGS in the building, a calibrated SOFC–CGS mathematical model was programmed using Visual Basic.NET. The research target building was modeled using Design Builder, and the one-year hourly energy consumption of the building was also predicted using this software. Design Builder as a calibrated software is made in England. This software was mainly used for energy analysis of the building. The calculation model of this software is EnergyPlus (Version 8.2.0, Department of Energy, Washington, USA), which is a calculation engine invented in America for analyzing the heating, cooling, lighting, ventilation, etc., of a building. There are several calculation engines for energy consumption prediction from which DOE-2 (Version 2.1E, Department of Energy, Washington, USA), DeST (Version 2.0, Tsinghua University, Beijing, China), and EnergyPlus are mainly used for the analysis of the energy consumption of buildings. Xin et al. compared the simulation performance among these three different calculation engines. Compared with EnergyPlus and DeST, DOE-2 is limited in the basic assumption of the heating, ventilation and air conditioning (HVAC) system calculations [29]. Therefore, the commercial software Design Builder with the calculation engine EnergyPlus was chosen for doing this research. The air pollutants of the research target building were calculated and compared under the conditions of using the traditional method of supplying energy to the building and new method of supplying energy to the building by referring to the air pollutant emission densities of electricity and natural gas in Korea. Finally, the environmental impact and efficiency analyses of operating the SOFC–CGS in the building were conducted.

2. Energy and Environmental Analysis of the Dormitory Building

2.1. Modeling of the Dormitory Building

There are a lot of dormitories for accommodating students near the campus of universities in Korea. Each room in the buildings typically can accommodate one or two students. Most of the dormitory buildings are constructed so that there is a supply of natural gas and electricity to the building. However, recently, some newly developed dormitory buildings have been constructed to use only electricity for all of the energy needs. One of these newly developed buildings was selected for this research. To predict the energy consumption of the building, a model of the building was made using Design Builder, and the 3D model and configuration are shown in Figure 2.

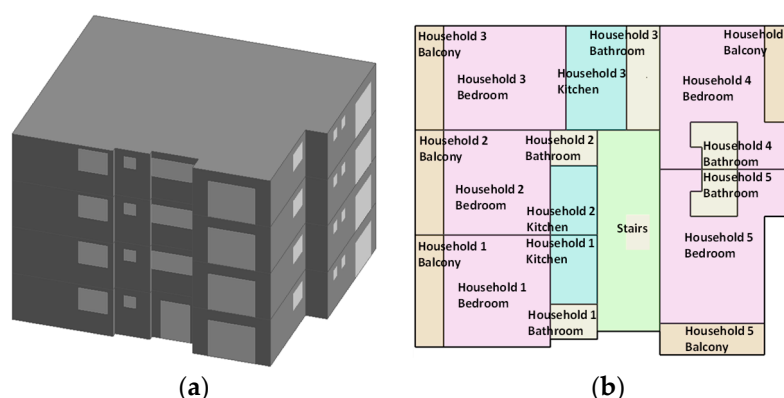


Figure 2. 3D model and configuration of the dormitory building. (a) 3D model; (b) Configuration.

According to the energy and environmental analysis of the dormitory building in a previous study [30], to predict the energy consumption of the building precisely, weather data of Busan, Korea, were acquired, and the occupancy schedule of different partitions of the building were referred from ASHRAE standard 90.2, 2010 [31]. Basic weather data were listed in Table 2. Moreover, the energy

consumption standard of a building in Korea was referred from the Korean Energy Agency to build the model. According to this standard, heating, cooling, resident density, lighting density, and equipment density were set as in Table 3 [32]. According to Korean Construction Law, the construction thermal specifications of external wall, internal wall, roof, and floor were set, as listed Table 3 [32–34]. Since this building uses only electricity, cooling and heating were both set from electricity. Table 3 briefly summarizes the building specifications of the dormitory building.

Table 2. Climate specifications of Busan.

Climate Specification	Value
Latitude	35°32' N
Longitude	129°19' E
Average annual temperature	14.05 °C
Average max annual temperature	35.4 °C
Average min annual temperature	−8.8 °C
Average annual relative humidity	63.40%
Average solar radiation	106.15 Wh/m ²
Average annual wind speed	1.93 m/s
Elevation above sea level	33 m

Table 3. Construction specifications.

Parameter	Specific Characteristic
Orientation	West to East
External wall	0.58 W/m ² K
Internal wall	2.92 W/m ² K
Roof	0.27 W/m ² K
Glazing	3.12 W/m ² K
Infiltration rate	0.3 ac/h
Ventilation rate	3 ac/h
Equipment	5.38 W/m ²
Lighting	3.88 W/m ²
Occupancy	0.054 people/m ²
HVAC/Heating	Dedicated hot water boiler (electricity)
HVAC/Cooling	Electricity from grid
Set point temperature	Summer 26 °C, Winter 22 °C

2.2. Energy and Environmental Analyses

According to the building model made using Design Builder in Section 2.1, the one-year energy consumption of the building was predicted. The energy analysis result showed that the one-year energy consumption of the building was 87,830.78 kWh when only electricity was used in the building. On the other hand, when natural gas and electricity were used together, the one-year electricity consumption was 18,013.7 kWh and the one-year natural gas consumption was 69,817.1 kWh.

To calculate the annual air pollutants emission of the building, the air pollutant emission densities of electricity and natural gas were referred from the Korea Environmental Industry and Technology Institute, as listed in Table 4 [32,35]. The one-year air pollutants of the building when only electricity was supplied and when natural gas and electricity were supplied together were calculated and compared. The environmental analysis result showed that the amount of CO₂ emission was much larger when the building used only electricity than when the building used electricity and natural gas together, as shown in Figure 3. On the other hand, emissions of other air pollutants, such as CH₄, N₂O, SO₂, CO, NO_x, and NMVOC, were much lower than CO₂ emission. This means that the building using natural gas and electricity together was much cleaner than the building using only electricity for all energy needs.

Table 4. Air pollutant emission densities of electricity and natural gas.

Air Pollutant	Electricity (kg/kWh)	Natural Gas (kg/kWh)
CO ₂	4.87×10^{-1}	3.94×10^{-2}
CH ₄	3.50×10^{-4}	2.01×10^{-4}
N ₂ O	1.35×10^{-6}	1.72×10^{-7}
SO ₂	0.00×100	4.22×10^{-4}
CO	5.00×10^{-5}	9.91×10^{-5}
NO _x	1.20×10^{-4}	5.67×10^{-4}
NMVOC	2.00×10^{-5}	1.04×10^{-6}

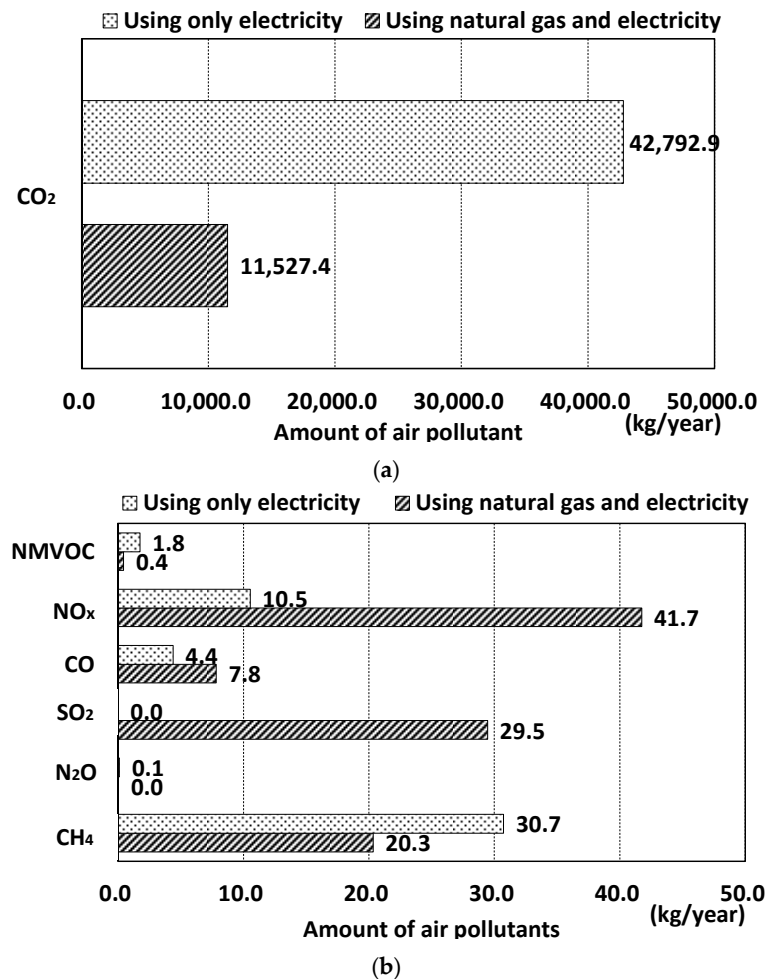


Figure 3. Comparison of air pollutant amounts between the building using only electricity and the building using electricity and natural gas together. (a) Comparison of amount of CO₂ emission (b) Comparison of amount of other air pollutants emission.

3. Modeling of SOFC–CGS

The residential fuel cell as a clean energy device is used widely in Japan. Since environmental problems including air pollution have been getting worse recently in Korea, implementation of the residential fuel cell as a clean energy device in buildings in Korea is necessary. Therefore, this research analyzed the efficiency and environmental impact of operating SOFC–CGS in a dormitory building in Korea, as mentioned in previous sections.

Typical approaches of fuel cell modeling in recent research were summarized in Table 5. In order to evaluate and optimize the performance of fuel cell, electrochemical models were developed to simulate the specific chemical and energy interaction inside the cell stack [36–38]. On the other hand,

in order to evaluate and improve the device operation efficiency and CO₂ reduction by using fuel cell for transportation or residential, fuel cell modeling by mainly using device efficiency was developed to simulate operating fuel cell in household or for EV [11,22,24]. In this research, the modeling of SOFC–CGS by mainly using the efficiency of the device was developed to simulate the application of SOFC–CGS in a dormitory building in Korea.

Table 5. Typical approaches of fuel cell modeling.

System	System Application	Model Application	Main Design Variables
SOFC [36]	Cell stack	Electrochemical model	Volumetric rate generated thermal energy, rate of production of species, area specific resistance
SOFC–CGS [37]	Stationary	Electrochemical model	Partial pressure of methane, reaction rate of steam reforming, cell temperature
SOFC [38]	Cell Stack	Electrochemical model	Partial pressure of species, anodic and cathodic charge-transfer coefficients, exchange current density
SOFC–CGS [22]	Stationary	Device efficiency	Efficiency of electricity generation, efficiency of heat collection, water temperature
SOFC–CGS [11]	Stationary/Transportation	Device efficiency	Electric demand of cafeteria, required electricity for EV charging, electric power generated by SOFC–CGS
SOFC–CHP/PEMFC–CHP [24]	Stationary	Device efficiency	Power generation efficiency of the fuel cell, heat recovery efficiency of the fuel cell, heat loss rate of the tank

3.1. Explanation of SOFC–CGS

Residential SOFC, as a clean energy supply device, has relatively low efficiency. Due to heat losses, the highest electricity generation efficiency of SOFC is about 46.4% [24,27]. To improve the efficiency of SOFC, SOFC–CGS was developed [24,25,27]. Heat losses from SOFC are collected to heat water, and a backup boiler is used for reheating the water to meet the demand temperature. A 28 L water storage tank was used in this system, as illustrated in Figure 4. SOFC uses natural gas to generate electricity to supply the electricity demand of a household. The heat losses of SOFC are collected and transferred to the water storage tank by a water tube. The limit temperature control of the storage tank is 65 °C, and the temperature of the storage tank is adjusted by controlling the water flow rate in the tube that collects heat from the SOFC. If the input water temperature through the radiator is higher than 34 °C, the radiator reduces the water temperature to 34 °C, then the water can enter the SOFC to collect heat. Hot water outputs from the storage tank to the household when hot water is needed. In this system, the city water temperature was set as 15 °C, and the hot water temperature demand was set as 40 °C. The output water temperature from the water mix device was set to be equal to or less than 33 °C. If the water output from the storage tank was equal to or less than 33 °C, hot water directly entered the backup boiler for reheating of the water to 40 °C and then the hot water at 40 °C was provided to the household. If the output water temperature from the storage tank was higher than 33 °C, the water mix device mixed city water and water from the storage tank to attain the temperature of 33 °C, and then, through the backup boiler, water was heated to 40 °C to supply the household. This system is illustrated as Figure 4. The specifications of the SOFC–CGS in this study are shown in Table 6, and the efficiency of electricity generation and heat collection of the SOFC–CGS are shown in Figure 5. The mathematical equation of the electricity generation efficiency is written as Equation (1). The efficiency of heat collection of the SOFC–CGS was constantly 31%.

$$EFF_{ElSup} = 0.6868LF^3 - 1.6829LF^2 + 1.4601LF. \quad (1)$$

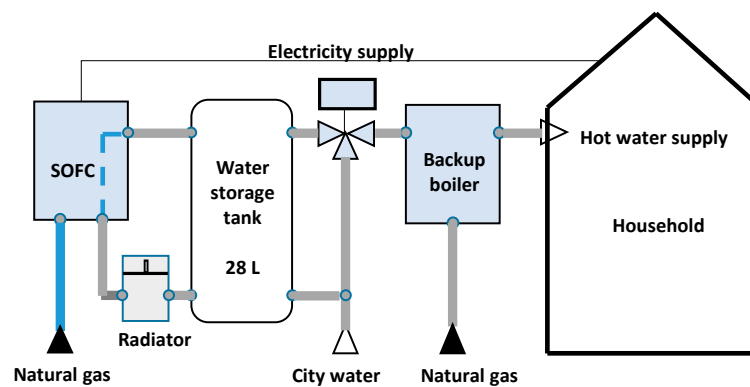


Figure 4. Working principle of the solid oxide fuel cell cogeneration system (SOFC-CGS).

Table 6. Specifications of the SOFC-CGS.

Type of Cell Stack	SOFC (Solid Oxide Fuel Cell)
Rated electrical output	700 W
Max running time	26 days
Standby time for start	1 day
Water tank volume	28 L
Reaction to overheating	Heat dissipation by radiator
Efficiency of heat collection	31%
Water temperature from tank to backup boiler	40 °C
Efficiency of electricity generation	46.4%

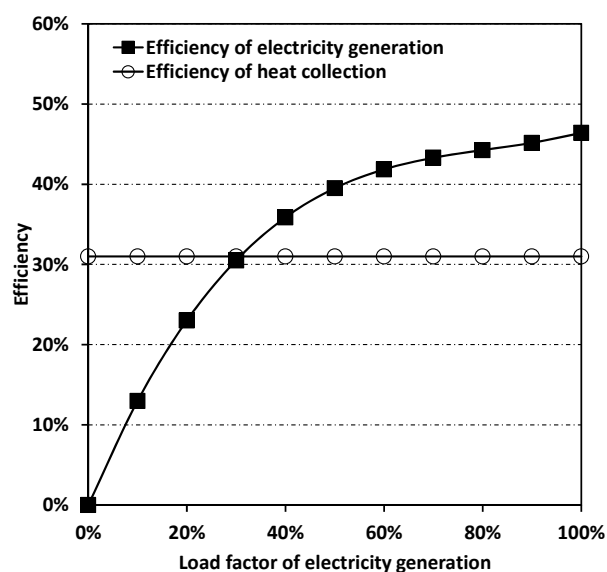


Figure 5. Efficiency of the SOFC-CGS.

In the equation, EFF_{ElSup} is the efficiency of electricity generation of the SOFC and LF is the load factor of electricity generation.

3.2. Mathematical Model of SOFC-CGS

In this study, the mathematical model of SOFC-CGS was referred from recent research from Kyushu University [25–27]. The electricity generation calculation follows the steps below. Firstly,

depending on the electricity generation tracking speed, the maximum electricity supply capability can be determined by Equation (2):

$$P_{\text{Supmax}} = -P_{\text{ElSup}} + V_{\text{ElSupSp}} I_{\text{tint}}, \quad (2)$$

where P_{Supmax} is the maximum electricity supply capability, P_{ElSup} is the amount of electricity generation, V_{ElSupSp} is the electricity generation tracking speed, and I_{tint} is the calculation time interval. Then, according to the household electricity demand, the electricity supply from SOFC can be determined. Following Equations (3) and (4), the amount of natural gas consumption by SOFC can be calculated:

$$LF = \frac{P_{\text{ElSup}}}{P_{\text{ElMax}}} \quad (3)$$

$$P_{\text{EhCell}} = \frac{P_{\text{ElSup}}}{\text{EFF}_{\text{ElSup}}}, \quad (4)$$

where LF is the load factor of electricity generation, P_{ElMax} is maximum electricity generation capacity of SOFC, P_{EhCell} is the amount of natural gas consumption of SOFC, and $\text{EFF}_{\text{ElSup}}$ is the efficiency of electricity generation. The amount of heat output from SOFC can be calculated by Equation (5):

$$P_{\text{HtSup}} = P_{\text{EhCell}} \text{EFF}_{\text{HtSup}}, \quad (5)$$

where P_{HtSup} is the amount of heat output from SOFC and $\text{EFF}_{\text{HtSup}}$ is the heat output efficiency of SOFC, which is 31%.

The water flow rate in the water tube that collects heat can be calculated using either Equation (6) or Equation (7). If the input water temperature through the radiator unit is higher than or equal to 34 °C, Equation (6) is used to calculate the water flow rate in water tube; otherwise, Equation (7) is used to calculate it.

$$V_{\text{wCell}} = \frac{P_{\text{HtSup}}}{C_w(T_{\text{out}} - 34)} \quad (6)$$

$$V_{\text{wCell}} = \frac{P_{\text{HtSup}}}{C_w(T_{\text{out}} - T_{\text{in}})}. \quad (7)$$

In the equations, V_{wCell} is the water flow rate in the water tube; P_{HtSup} is the amount of heat supply from SOFC; T_{out} is the target output water temperature from the SOFC, which was set as 65 °C in this study; T_{in} is the input water temperature to the radiator unit; and C_w is the specific heat of water.

If the water temperature is higher than 34 °C, the heat dissipation of the radiator unit is determined by Equation (8); otherwise, the heat dissipation of the radiator unit is zero:

$$P_{\text{Rad}} = V_{\text{wCell}} C_w (T_{\text{out}} - T_{\text{in}}), \quad (8)$$

where P_{Rad} is the heat dissipation from the radiator unit. The amount of heat output from the backup boiler is determined by Equation (9), and the amount of gas used in the backup boiler is calculated from Equation (10):

$$P_{\text{BBSup}} = \text{Vol}_{\text{HwDmd}} C_w (T_{\text{Dmd}} - T_{\text{BBin}}), \quad (9)$$

$$P_{\text{BBUse}} = \frac{P_{\text{BBSup}}}{\text{EFF}_{\text{BB}}}, \quad (10)$$

where P_{BBSup} is the amount of heat output from the backup boiler, P_{BBUse} is the amount of gas used in the backup boiler, T_{Dmd} is the water temperature demand from the household, T_{BBin} is the input water temperature to the backup boiler, $\text{Vol}_{\text{HwDmd}}$ is the amount of hot water demand from the household, P_{BBUse} is the amount of gas used in the backup boiler; and EFF_{BB} is the working efficiency of the backup boiler, which was set as 95% in this study.

The calculation flow of the program and the input data are shown as Figure 6 and Table 7.

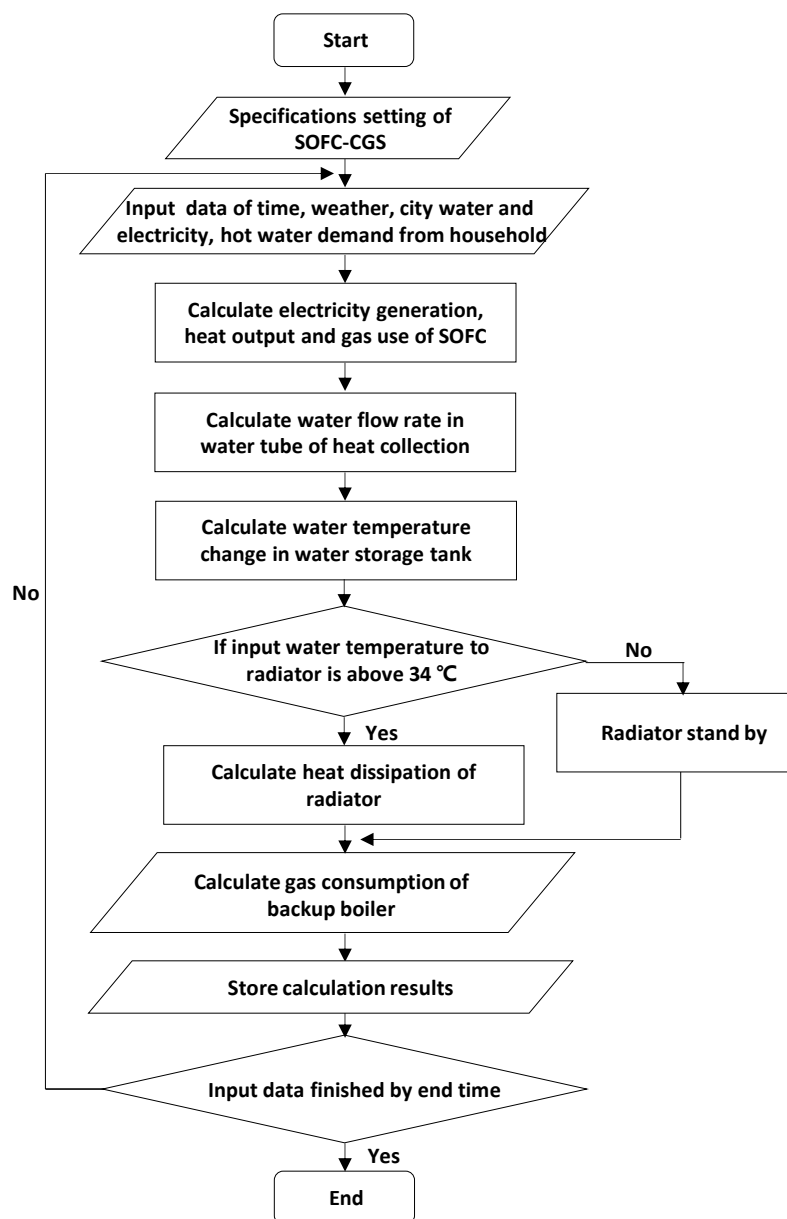


Figure 6. Calculation diagram of the program.

Table 7. Input data of the program.

Input Data	Unit/Value
Electricity demand	W
Hot water demand	L/Time unit
Setting temperature of backup boiler	40 °C
Outside temperature	Data from ASHRAE
Temperature of city water	15 °C
Temperature of hot water demand	40 °C

4. Simulation of Operating SOFC–CGS in the Dormitory Building

As mentioned in Section 2, the energy consumption for heating the research target building in winter was significant. Since using electricity from the public power plant results in much more air

pollution than using natural gas for heating and because the efficiency of directly using natural gas for heating was much higher than that of using natural gas to generate electricity for heating by the SOFC, in this research, energy for heating was not considered as being supplied from the SOFC. Aside from heating, the SOFC–CGS provides electricity and hot water to the households.

The research target building had four floors, and each floor had the same structure with five households. As the energy consumption of each household was predicted by the calibrated commercial software Design Builder, the energy consumption pattern and amount were the same for each floor. Thus, the first floor was chosen for this research. As mentioned previously, there were five households in first floor, and the energy consumption pattern was similar among the five households in the first floor. According to schedule of ASHRAE standard for residential house [31], the electricity and hot water consumption patterns of representative dates of each season of household 1 in the first floor are shown as Figure 7. As heating energy was provided directly by natural gas, it was not considered in simulating the operating SOFC–CGS. The yearly energy consumption of each household in the first floor is shown as Figure 8.

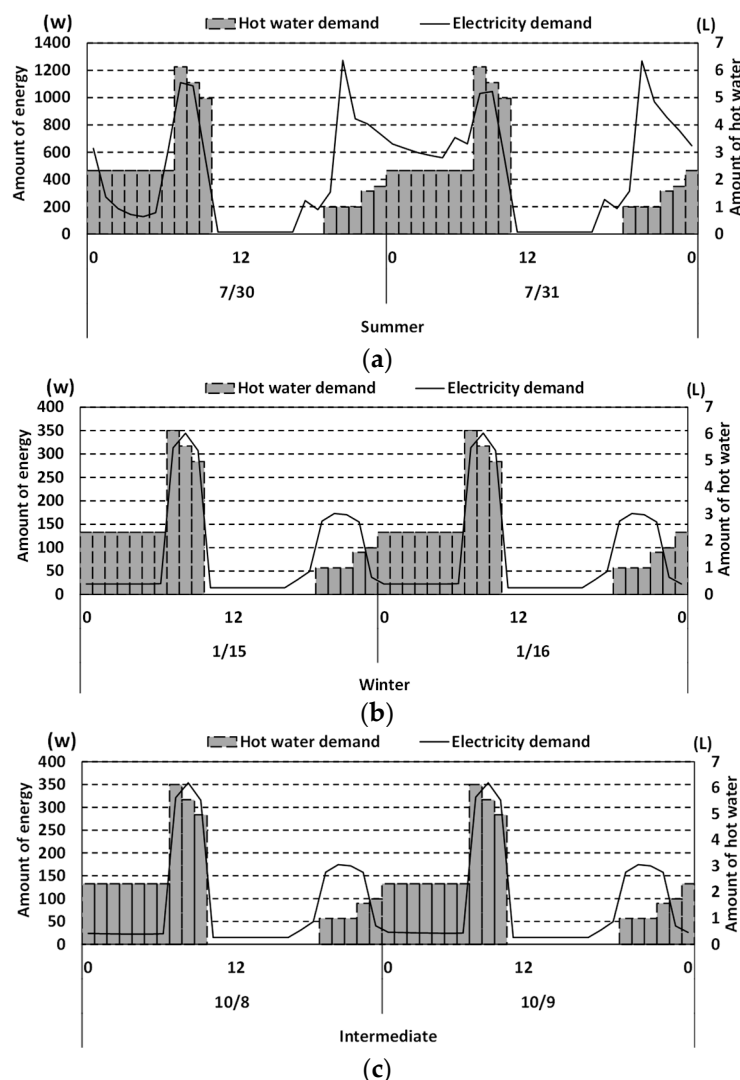


Figure 7. Representative daily data of electricity demand and hot water demand of household 1 in each season. (a) Data in summer; (b) Data in winter; (c) Data in intermediate seasons.

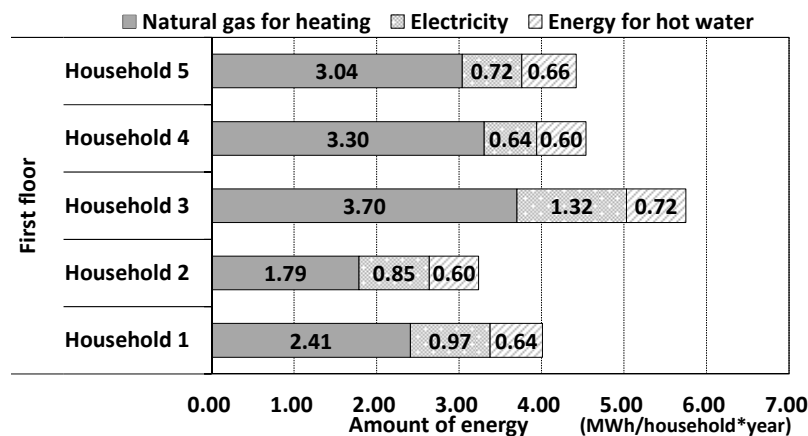


Figure 8. Yearly energy consumption of each household in the first floor.

To improve and analyze the efficiency of SOFC–CGS, one SOFC–CGS was simulated to operate in either only one household or in multi-households (two or three households). According to the yearly energy consumption of each household, as shown in Figure 8, household 2 ranked the lowest and household 3 ranked the highest. Therefore, in order to form a balance, households 2 and 3 were simulated as sharing one SOFC–CGS, and households 1, 4, and 5 were simulated as sharing one SOFC–CGS. Hourly data of electricity demand, electricity generation, and heat output from the SOFC and the heat reduction amount from the radiator at representative days in the year in summer are shown as Figures 9–11 below.

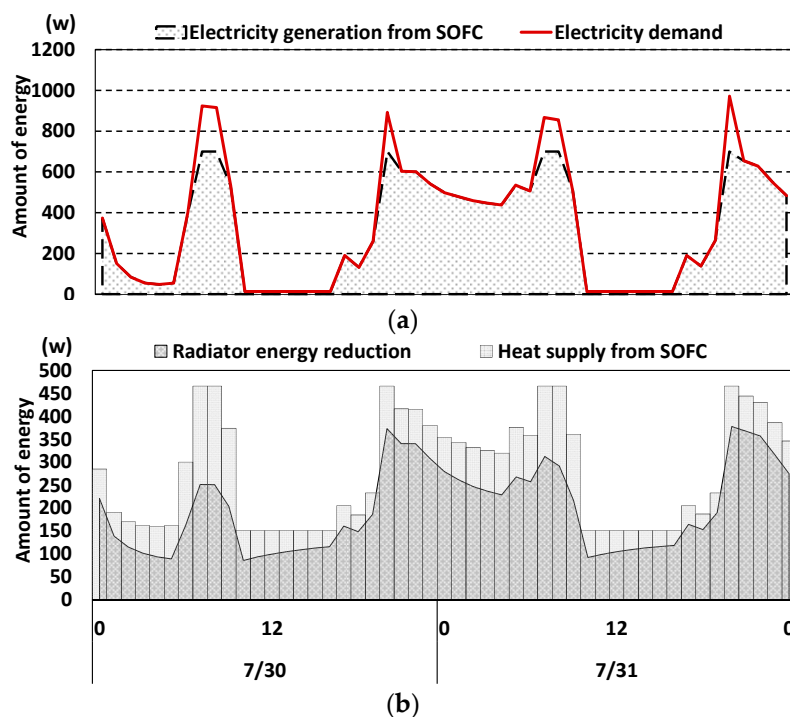


Figure 9. Hourly simulation data of household 2. (a) Data of electricity generation and electricity demand; (b) Data of heat reduction and heat supply.

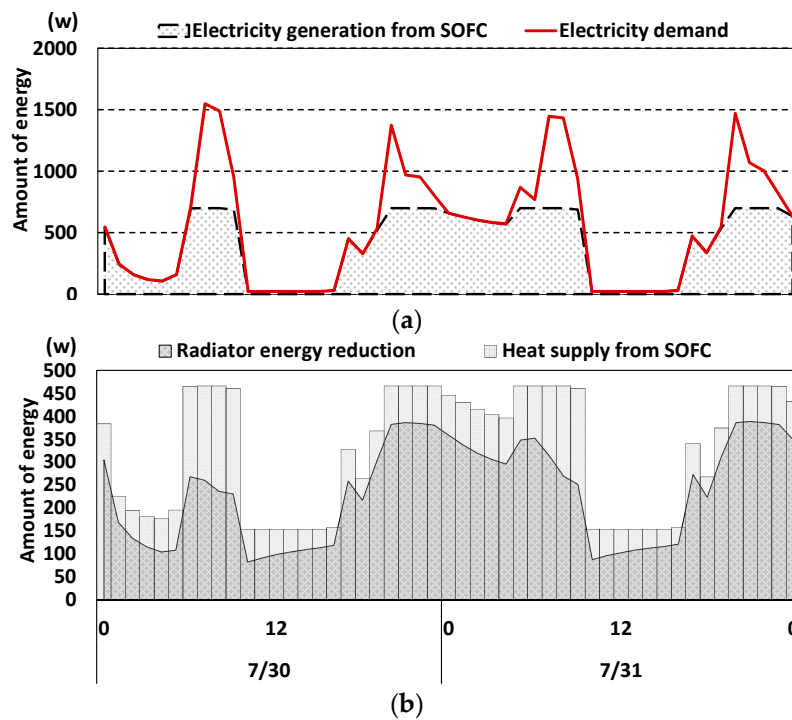


Figure 10. Hourly simulation data of household 3. (a) Data of electricity generation and electricity demand; (b) Data of heat reduction and heat supply.

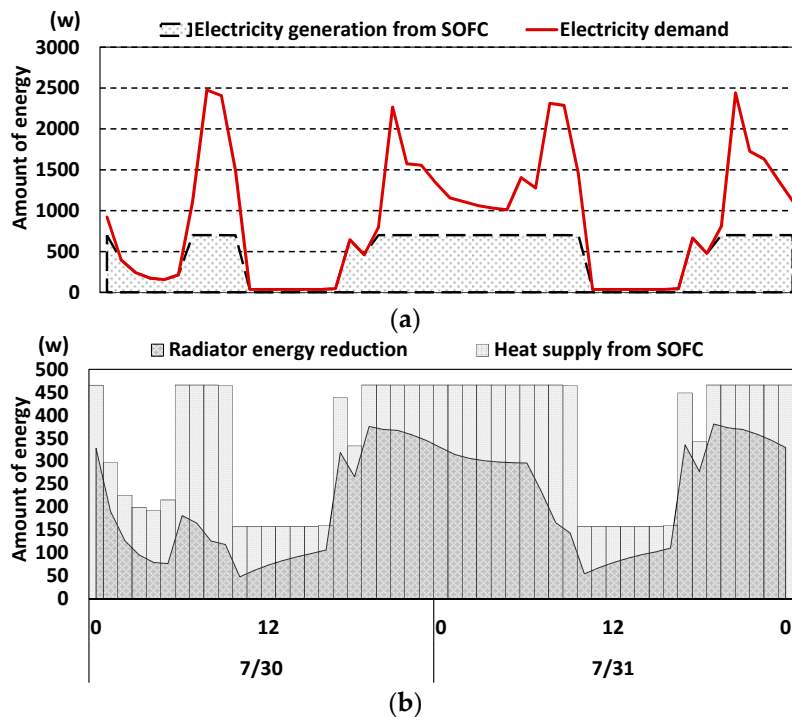


Figure 11. Hourly simulation data of households 2 and 3. (a) Data of electricity generation and electricity demand; (b) Data of heat reduction and heat supply.

As the data of the simulation results were large, the simulation results of households 2 and 3 were selected for presentation in this research. Figures 9 and 10 show the simulation results when operating one SOFC–CGS for one household. Figure 11 shows the simulation results when sharing one SOFC–CGS by multi-households. The load factor of SOFC–CGS was increased when multi-households

share one SOFC–CGS, as in Figure 11. This means that the electricity generation efficiency of SOFC–CGS was improved. Additionally, the ratio of heat reduction amount by the radiator was reduced when SOFC–CGS was shared by multi-households, as shown in Figure 11, which means that the efficiency of heat usage for hot water was increased.

5. Analysis of Efficiency and Environmental Impact of SOFC–CGS

5.1. Analysis of SOFC–CGS Efficiency

The yearly energy consumptions of simulating the operation of one SOFC–CGS to one household and multi-households are shown as Figure 12. The natural gas consumption by SOFC, electricity generation by SOFC, purchased electricity, and natural gas consumption by the backup boiler were higher when simulating the operation of one SOFC–CGS for multi-households than when simulating for one household. The electricity consumption by SOFC was constant because electricity was only used when the SOFC started or restarted. Increasing electricity generation led to increasing efficiency of electricity generation by SOFC. The reason for this was that sharing one SOFC–CGS to multi-households led to increasing electricity and hot water demand for the one SOFC–CGS.

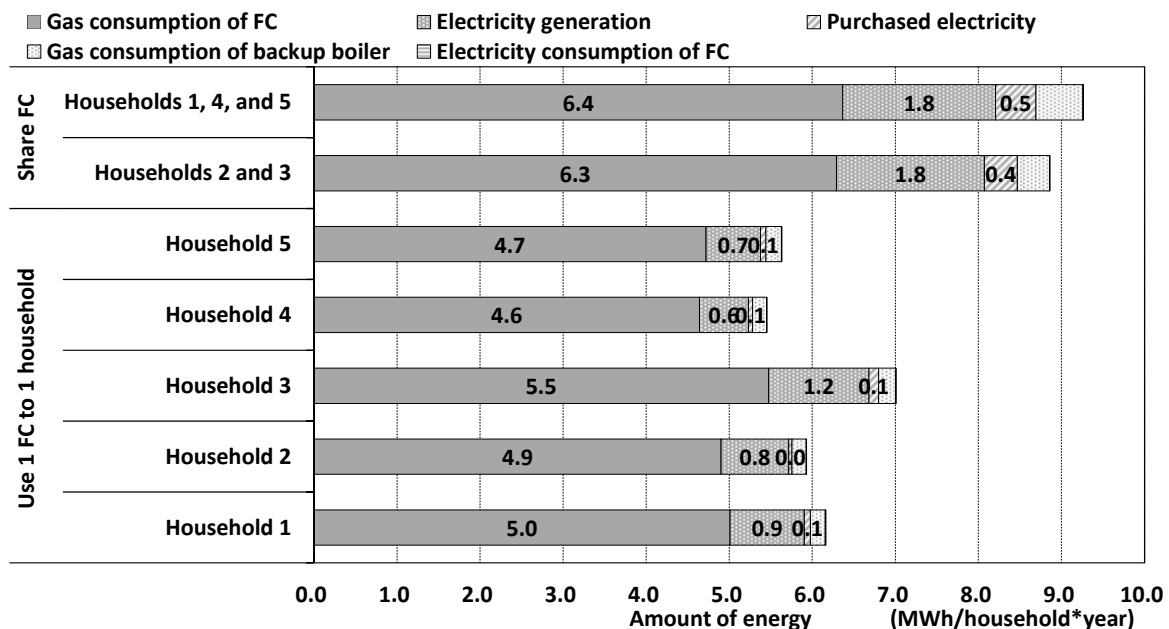


Figure 12. Yearly energy consumptions of simulating one SOFC–CGS for one household and multi-households.

According to Figure 13, the electricity generation efficiency of SOFC ranged from 13% to 22% and the heat usage efficiency ranged from 22% to 23% when simulating the operation of one SOFC–CGS for one household. The efficiency of electricity generation of SOFC was increased to range from 28% to 29% and the heat usage efficiency was increased to range from 24% to 25% when multi-households share one SOFC–CGS. The percentages of losses from different components of SOFC–CGS of simulating operation of one SOFC–CGS to one household and sharing one SOFC–CGS by multi-households are compared in Figure 14. The losses in fuel cell and radiator were decreased when multi-households share one SOFC–CGS. In another aspect, sharing one SOFC–CGS by multi-households increased the electricity demand from the public power plant, which leads to more air pollution. The specific environmental analysis is shown in Section 5.2.

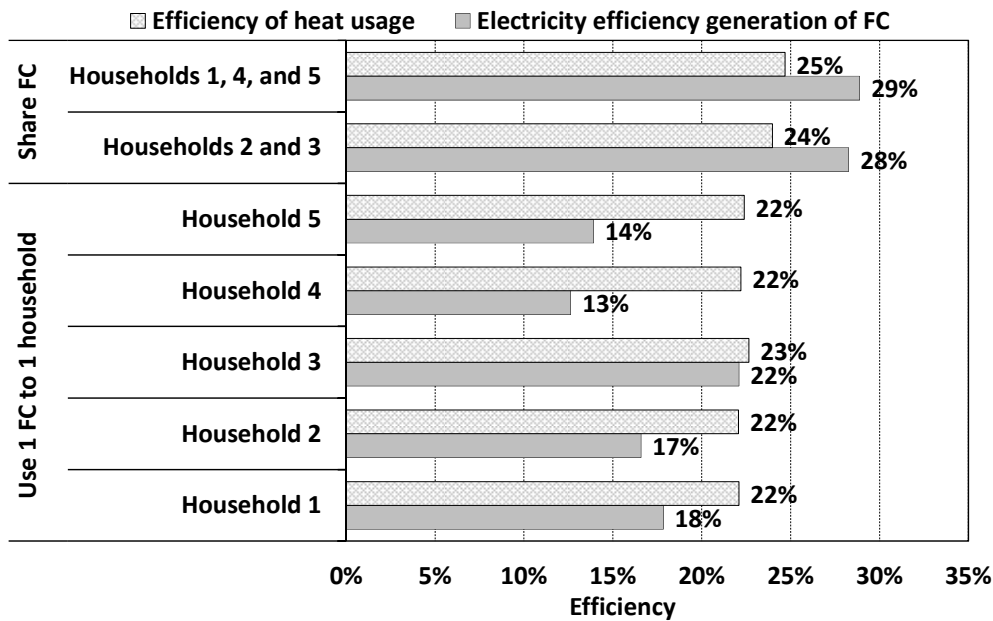


Figure 13. Yearly electricity generation and heat output efficiencies of simulating using one SOFC cogeneration system for one household and multi-households.

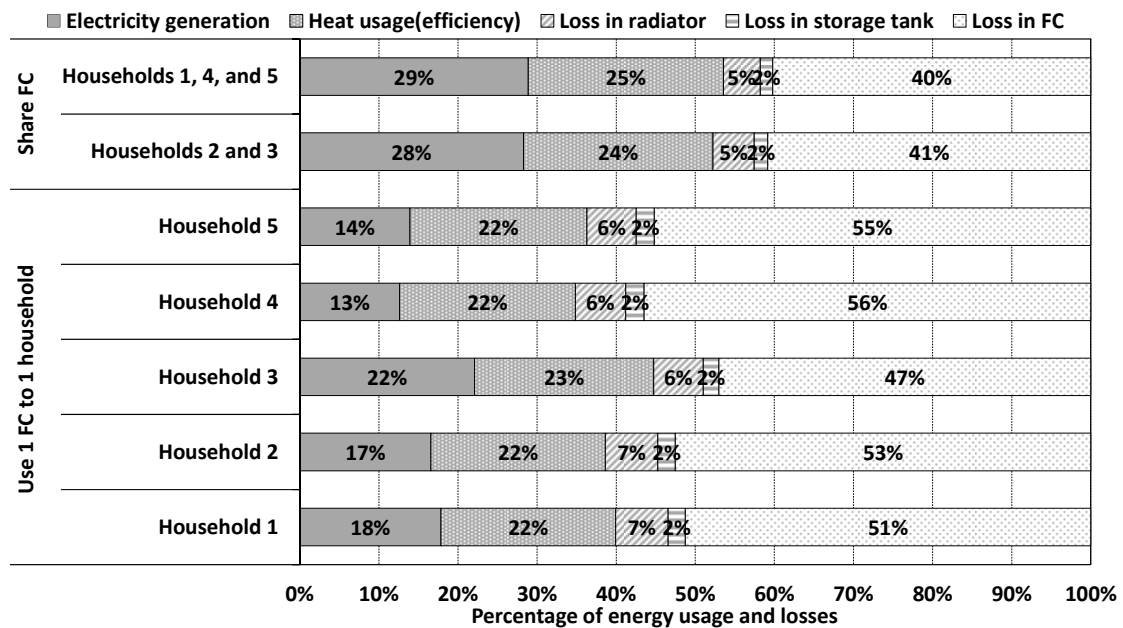


Figure 14. Yearly energy losses of simulating using one SOFC-CGS to one household and multi-households.

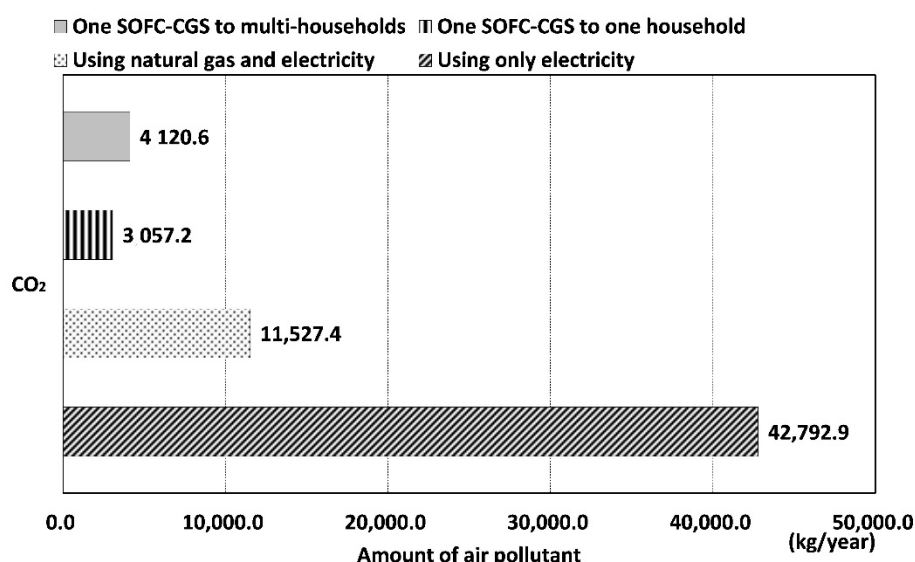
5.2. Analysis of Environmental Impact of SOFC-CGS

Including the two previous cases of energy supply types in the building in Section 2, four different cases of energy supply types are explained and summarized in Table 8. In the first case, only electricity was supplied to the building, while in the second case, natural gas and electricity together were supplied. According to the analysis result, the second energy supply type emitted a relatively smaller amount of air pollutants than the first type and the efficiency of using natural gas directly by combustion was much higher than using natural gas by SOFC for heating. Therefore, in the third case, one SOFC-CGS was applied to one household under the second energy supply type, and in the fourth case, one SOFC-CGS was applied to multi-households under the second energy supply

type. The environmental analysis for the entire building (four stories) under the four different cases of energy application types is shown as Figure 15. According to the result of the environmental analysis, the amount of CO₂ emission was most significant in the case of using only electricity in the building. The CO₂ emission of the second case, using natural gas and electricity together in the building, was much lower than in the case of using only electricity in the building. Under the energy supply type of the second case, when SOFC–CGS was simulated as operating in the building, the CO₂ emission was significantly reduce to range from 3057.2 to 4120.6 kg/year. The case of operating one SOFC–CGS for one household gave the lowest CO₂ emission. Due to the purchased electricity from the public power plant was increased from the third case to the fourth case as shown in the energy analysis in Figure 12, the fourth case resulted in a higher air pollutants emission than the third case. However, the case of sharing one SOFC–CGS among multi-households had a higher system efficiency than the case of operating one SOFC–CGS for one household, as indicated by the analysis result in Section 5.1. In another aspect, the difference of CO₂ emission between cases three and four was not significant, as in Figure 15; therefore, the case of sharing one SOFC–CGS among multi-households was recommended. According to Figure 15, the emission amounts of the pollutants other than CO₂ of the four different cases were much lower than the CO₂ emissions of the four different cases.

Table 8. Explanation of cases for environmental analysis.

Case Number	Case Name	Energy for Heating/Hot Water	Energy for Other Needs in Household
1	Using only electricity	Purchased electricity from power plant	Purchased electricity from power plant
2	Using natural gas and electricity	Direct natural gas (heating and hot water)	Purchased electricity from power plant
3	One SOFC–CGS for one household	Direct natural gas (heating)	Individual SOFC–CGS for one household and purchased electricity from power plant
4	One SOFC–CGS to multi-households	Direct natural gas (heating)	Shared SOFC–CGS for multi-households and purchased electricity from power plant



(a)

Figure 15. Cont.

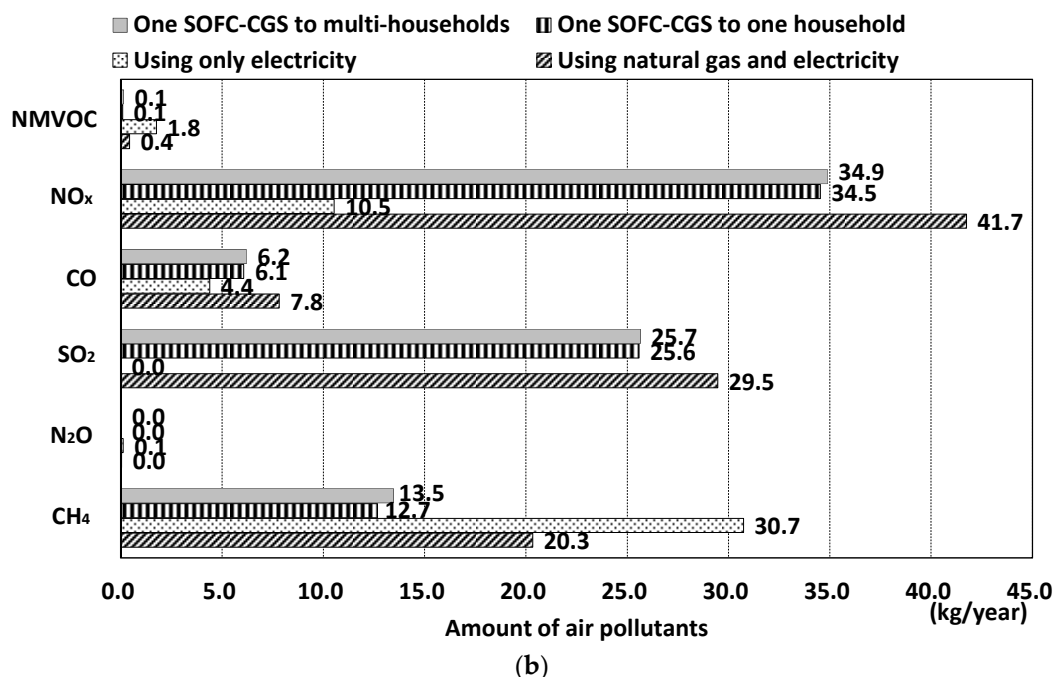


Figure 15. Comparison of air pollutant amounts of the building under the four different energy supply types. (a) Comparison of amount of CO₂ emission (b) Comparison of amount of other air pollutants emission.

6. Conclusions

Residential SOFC, as a clean energy device, continues to be researched by researchers in the field of architecture. However, as the efficiency of SOFC is relatively low, SOFC–CGS has been studied recently by many researchers. In this research, the environmental and efficiency impacts of operating SOFC–CGS in a dormitory building in Korea were analyzed. As a newly developed building, the research target building was constructed with electricity as the only energy resource. Analysis of this strategy was required. Firstly, in this study, the environmental impact was compared between the cases of using only electricity (new way) and using electricity and natural gas (traditional way) in the building. The analysis result showed that the traditional way of energy supply type in the building emits less air pollution than the new way. Secondly, based on the traditional energy supply type, operating SOFC–CGS in the building was simulated. The efficiency and environmental impact were analyzed, and these were compared between the cases of simulating one SOFC–CGS in one household and sharing one SOFC–CGS among multi-households. The specific conclusions are listed below.

(1) The comparison analysis between supplying only electricity to the building and supplying electricity and natural gas together showed that supplying electricity and natural gas together results in much less air pollution than supplying only electricity.

(2) Under the energy supply type of supplying electricity and natural gas together to the building, SOFC–CGS was simulated in the building under the conditions of operating one SOFC–CGS in one household and sharing one SOFC–CGS among multi-households. The electricity generation efficiency of SOFC ranged from 13% to 22% and the heat usage efficiency ranged from 22% to 23% when simulating operation of one SOFC–CGS in one household. The electricity generation efficiency of SOFC increased to range from 28% to 29% and the heat usage efficiency increased to range from 24% to 25% when multi-households shared one SOFC–CGS.

(3) The four different cases of energy supply type for environmental analysis were summarized in Table 8. According to the results of the environmental analysis, the CO₂ emission was significantly reduced from 11,527.4 kg/year to 3057.2 kg/year when simulating the operation of one SOFC–CGS in one household under the energy supply type of case two. On the other hand, the CO₂ emission

was significantly reduced from 11,527.4 kg/year to 4120.6 kg/year when simulating the sharing of one SOFC–CGS among multi-households. The emission amounts of pollutants other than CO₂ of the four different cases were much lower than the CO₂ emissions of the four different cases.

(4) The difference of CO₂ emission between a simulating operation of one SOFC–CGS in one household and the sharing of one SOFC–CGS among multi-households was not significant. Meanwhile, simulating the sharing one SOFC–CGS among multi-households led to higher efficiency than simulating the operation of one SOFC–CGS in one household. Therefore, sharing one SOFC–CGS among multi-households in a dormitory building is recommended.

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Abbreviations

SOFC	Solid oxide fuel cell
SOFC–CGS	Solid oxide fuel cell cogeneration system
LNG	Liquefied Natural Gas
CHP	Combined heat and power
DC	Direct current
AC	Alternating current
EV	Electric vehicle
SOFC–CHP	Solid oxide fuel cell combined heat and power
GHG	Greenhouse gas
HVAC	Heating, Ventilation and Air Conditioning
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
PEMFC–CHP	Proton exchange membrane fuel cell combined heat and power

Nomenclatures

EFF_{ElSup}	Efficiency of electricity generation
LF	Load factor of electricity generation
P_{Supmax}	Maximum electricity supply capability
P_{ElSup}	Amount of electricity supplication
$V_{ElSupSp}$	Electricity generation tracking speed
I_{tint}	Time interval
P_{ElMax}	Maximum electricity generation capacity of SOFC
P_{EhCell}	Amount of natural gas consumption of SOFC
P_{HtSup}	Amount of heat output from SOFC
EFF_{HtSup}	Heat output efficiency of SOFC
V_{wCell}	Water flow rate in the water tube
T_{out}	Target output water temperature from the SOFC
T_{in}	Input water temperature to the radiator unit
C_w	Specific heat of water
P_{Rad}	Heat dissipation from the radiator unit
P_{BBSup}	Amount of heat output from the backup boiler
P_{BBUse}	Amount of gas used in the backup boiler
T_{Dmd}	Water temperature demand from the household
T_{BBin}	Input water temperature to the backup boiler
Vol_{HwDmd}	Amount of hot water demand
EFF_{BB}	Working efficiency of the backup boiler

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