

Article

An Economic and Environmental Assessment Model for Selecting the Optimal Implementation Strategy of Fuel Cell Systems—A Focus on Building Energy Policy

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Abstract: Considerable effort is being made to reduce the primary energy consumption in buildings. As part of this effort, fuel cell systems are attracting attention as a new/renewable energy systems for several reasons: (i) distributed generation system; (ii) combined heat and power system; and (iii) availability of various sources of hydrogen in the future. Therefore, this study aimed to develop an economic and environmental assessment model for selecting the optimal implementation strategy of the fuel cell system, focusing on building energy policy. This study selected two types of buildings (*i.e.*, residential buildings and non-residential buildings) as the target buildings and considered two types of building energy policies (*i.e.*, the standard of energy cost calculation and the standard of a government subsidy). This study established the optimal implementation strategy of the fuel cell system in terms of the life cycle cost and life cycle CO₂ emissions. For the residential building, it is recommended that the subsidy level and the system marginal price level be increased. For the non-residential building, it is recommended that gas energy cost be decreased and the system marginal price level be increased. The developed model could be applied to any other country or any other type of building according to building energy policy.

Keywords: fuel cell system; molten carbonate fuel cell (MCFC); life cycle cost; life cycle CO₂; building energy policy; different type of buildings

1. Introduction

Energy depletion and global warming due to careless use of primary energy have resulted in a global environmental crisis [1–3]. Among the various sectors that cause environmental load, the building sector consumes a considerable part of the global primary energy, and thus various efforts are being made globally to solve this issue [4–14]. Among the different measures to save primary energy in the building sector, new/renewable energy systems (NREs), as distributed energy supply systems, allow regional peak loads to be mitigated and building energy consumption to be reduced [15–28]. In fact, as most of the commercially available fuel cell systems rely on fossil fuels (*i.e.*, petroleum, natural gas, and coal) for hydrogen, they are not NREs in a strict sense. However, considering the fact that various efficient methods for getting hydrogen from eco-friendly materials (*i.e.*, biomass, ethanol, minerals and water) are currently being developed in many countries, fuel cell systems should be regarded as future NREs [29–34]. Particularly, compared to the other NREs, the fuel cell system has the advantages of being barely affected by the climate and of requiring the smallest area to generate electricity. Furthermore, the fuel cell system is a combined heat and power system with high energy production efficiency. The South Korea government is currently promoting fuel cell systems as a core green technology and has announced hydrogen infrastructure development plan which aims to develop such an infrastructure by 2030 using installed gas pipelines. Although the hydrogen infrastructure in South Korea is at an early stage, the growth potential of fuel cell systems is much higher than that on any other type of NRE [35–38].

Despite these advantages, however, the electricity generation from fuel cell systems in South Korea as of 2011 was merely 63,344 tons of oil equivalent (TOE), which is only about 32% of the electricity generation from photovoltaic systems (158,095 TOE). Furthermore, out of the total energy generation from fuel cell systems, only 2,614 TOE (4.3%) was introduced to buildings for their own use [39].

The reasons for the lower distribution of the energy from fuel cell systems can be categorized into two groups. Firstly, the fuel cell system market structure has focused on small scale fuel cell systems (*i.e.*, PEMFC systems or SOFC systems). In South Korea, however, large-scale buildings such as multi-family housing complexes and multi-use office complexes account for most of the building types [40,41], thus in South Korea, in the densely populated areas, large-scale fuel cell systems such as molten carbonate fuel cell (MCFC) systems should be considered rather than PEMFC systems or SOFC systems [42,43]. Secondly, building energy policies have failed to fully promote fuel cell systems in the building sector. The economic and environmental effects of a fuel cell system in a building are seriously affected by external factors such as the building energy policies. Therefore, building energy policies should be attractive for potential consumers to buy a new technology or system. The "Green Deal" program in the UK and the "kFw building rehabilitation" program in Germany are examples of successful cases which help consumers to make a profit on the installation of energy efficiency measures and NREs. In South Korea, however, such financing or incentive schemes are at an early stage (*i.e.*, the "Green Remodeling" program). Moreover, other established support schemes (*i.e.*, standard of energy cost calculation, and government subsidy levels) are not attractive enough to induce consumers to buy a NREs. Since the building energy policies in South Korea depend on the type of building, the introduction of the same fuel cell system in different kinds of buildings would result in different economic and environmental analysis results [44–53]. Therefore, in

implementing a fuel cell system, it is necessary to apply the appropriate building energy policy by considering the characteristics of different building types. To address these challenges, the focus in this study is to show that an optimal implementation strategy for fuel cell systems can be obtained when an economic and environmental assessment model is developed, focusing on building energy policy.

This study was conducted as a follow-up study to Hong *et al.* [54], which was focused on MCFC as one of the fuel cell systems. Hong *et al.* [54] proposed a framework for establishing the optimal implementation strategy of a fuel cell system for a multi-family housing complex. Meanwhile, this study tried to improve the established framework into a user-friendly model in which the economic and environmental effects of a fuel cell system in different types of buildings (*i.e.*, residential building and non-residential building) can be analyzed. Additionally, this model was designed to reflect the effect of building energy policies on the implementation of a fuel cell system in a building. Therefore, it can be used not only to establish the optimal implementation strategy of a fuel cell system in different types of buildings, but also to propose suitable building energy policies according to the building type.

2. Literature Review

There have been various studies on the economic and environmental effects of fuel cell systems in a building from the following two perspectives: (i) the economic effects of the fuel cell system were analyzed under various conditions; and (ii) the environmental effects of the fuel cell system in a building were analyzed.

First, the economic effects of the fuel cell system were analyzed under various conditions [55–61]. Mahlia *et al.* [55] assessed the economic effect of a 1 kW PEMFC system for a household in Malaysia. LCC analysis was conducted in terms of net present value (NPV) and break-even point (BEP). It was shown that there was no cost effective scenario in terms of NPV and BEP, even though the PEMFC could reduce the primary energy usage by up to 30%–40%. The results also indicated that the initial construction cost of PEMFC had to be reduced to MYR 2000/kW. Guizzi *et al.* [56] analyzed the economic effect of a PEMFC for a data center in Italy. An annual energy cost saving analysis was conducted. It was determined that the annual energy cost could be reduced by more than 47% compared to the conventional energy supply system. Oh *et al.* [57] conducted an economic assessment of a 1 kW PEMFC for a household in South Korea. The unit cost of electricity was estimated by considering a thermo-economic analysis and the economic benefit achieved by introducing the PEMFC in the household. The results revealed that energy cost savings of approximately 25% could be achieved by introducing the PEMFC in the spring and fall, which leads to a total of annual energy cost savings of up to 20%.

Second, various studies have focused on the environmental effects of the fuel cell system in a building [62–68]. Wakui *et al.* [62] conducted an environmental assessment of PEMFCs in households in terms of primary energy savings. A power interchange operation scheme was developed to improve the primary energy saving effect and a primary energy saving analysis was conducted on various scales of the PEMFC operating size. It was determined that the optimal operating size of a PEMFC for a household was 0.6 kW and the annual primary energy saving was 17% compared to the conventional energy supply system. Aki *et al.* [63] assessed the environmental effects of PEMFCs in several

households in terms of primary energy savings and CO₂ mitigation. The analysis was conducted based on a proposed energy supply system where the energy produced by the PEMFC was shared among several households. The results revealed that the primary energy saving and the CO₂ mitigation varied by season and the annual average primary energy saving and CO₂ mitigation were 6% and 11%, respectively. Fong *et al.* [64] proposed two operating schemes of a SOFC system for a high-rise building and evaluated the environmental performance in terms of CO₂ mitigation and electricity savings on the yearly basis. In the case of the first operating scheme where the electricity demand of a given building was fully met by SOFC, the CO₂ mitigation and electricity savings were 51.4% and 7.1%, respectively. In the case of the second operating scheme where the electricity demand of a given building was partly met by SOFC, the CO₂ mitigation and electricity saving were 23.9% and 2.8%, respectively.

In summary, there are several limitations in the previous studies: (i) most previous studies were limited to the analysis of a fuel cell system for a small scale facility such as a household; (ii) there are no previous study focusing on the comparison analysis of the economic and environmental assessments by different types of buildings from the perspective of building energy policy; and (iii) there are no previous studies on the optimal fuel cell system design alternative in terms of integrated economic and environmental assessment. This study aimed to solve these limitations.

3. Materials and Methods

This study aimed to develop an economic and environmental assessment model for selecting the optimal implementation strategy for a fuel cell system, focusing on building energy policy. The developed model consists of four parts: (i) Part 1: Establishment of comparison type of building and calculation of energy demand; (ii) Part 2: Establishment of the implementation strategies of the fuel cell system; (iii) Part 3: Analysis of energy demand and supply by implementation strategies; and (iv) Part 4: LCC and LCCO₂ analysis. In addition, a graphical user interface was developed by integrating the information from Part 1 into Part 4. Detailed descriptions follow.

3.1. Part 1: Establishment of Comparison Type of Building and Calculation of Energy Demand

3.1.1. Establishment of Comparison Type of Building from the Perspective of Building Energy Policy

To conduct economic and environmental analysis of the fuel cell system, it is necessary to consider the characteristics and the energy demand of a given building from the perspective of the building energy policy. This is because even with identical monthly energy demands, the economic and environmental analysis results can differ according to the building energy policy. In this study, the energy policies which aim to promote NREs in a building for the purpose of reducing building energy consumption were defined as the building energy policies. Building energy policies in South Korea are specifically divided into four categories:

- Certification of NREs: this certification scheme was designed to guarantee the quality of systems manufactured or imported to enhance user reliability. Certification of NREs focuses on promoting the commercialization of NRE technologies (*i.e.*, solar thermal, solar PV, wind power, geothermal, and fuel cell) in buildings;

- NREs mandatory use for public buildings: under this mandatory scheme, new buildings of public institutions (*i.e.*, administrative bodies, local autonomous entities, and state-run companies), the floor area of which exceeds 1,000 square meters, are obliged to use more than 10% of their total expected energy consumptions from installed NREs;
- The standard of energy cost calculation: for the purpose of acceleration of NREs deployment, the government provides a special fuel unit price (*i.e.*, a special unit price for gas only used for fuel cells) and a system marginal price (SMP) electricity market price applied in transactions involving electricity generated from non-fossil fuels, for NREs users to participate in the utility market; and
- The standard of government subsidy: the government provides subsidies for NREs users to promote NREs deployment. Those government subsidy schemes are classified into two categories which are the test-period deployment subsidy program and the general deployment subsidy program. The test-period deployment subsidy program aims to support the newly developed technologies and systems to advance into the market. On the other hand, the general deployment subsidy program aims to activate the market for NREs which already have been commercialized (*i.e.*, solar PV, wind power, geothermal, and fuel cell).

Among these building energy policies, the government subsidy and energy cost calculation standards should be considered in implementing the fuel cell system to a building for the two reasons discussed below. First, the fuel cell system is a combined heat and power system that can simultaneously produce electricity and heat energy. Thus, in conducting the economic and environmental analysis, the electricity and gas cost should be calculated simultaneously. In South Korea, the standard of energy cost calculation can be generally divided into that for residential buildings and that for non-residential buildings. Especially, a progressive tax should be considered to calculate the electricity cost for residential buildings. In a progressive tax, as the energy consumption of residential building increases, a higher unit price of electricity is applied for the electricity end-user in the calculation of electricity costs of the month (*i.e.*, \$0.055/kWh is applied until the first use of 100 kWh, \$0.094/kWh is applied from 100 kWh to 200 kWh, and \$0.139/kWh is applied from 200 kWh to 300 kWh). Therefore, it is necessary to consider the type of building in calculating the building's energy cost.

Second, the fuel cell system has a higher initial construction cost per unit capacity than other NREs. Thus, government subsidies should be considered to ensure the economic feasibility of the fuel cell system. Residential buildings can receive government subsidies through the *One Million Green Homes Program*. On the other hand, non-residential building can receive government subsidies through a *Building Support Program*.

Therefore, in this study, residential building and non-residential building were established as the comparison type of building from the perspective of the building energy policy (refer to Figure 1). In addition, this study selected the “Oksu” multi-family housing complex (“O” multi-family housing complex) as a representative type of residential building and the “Yonsei” multi-use office complex (“Y” multi-use office complex) as a representative type of non-residential building (refer to Figure 1 and Table 1) [54].

Figure 1. Graphical user interface of Part 1.

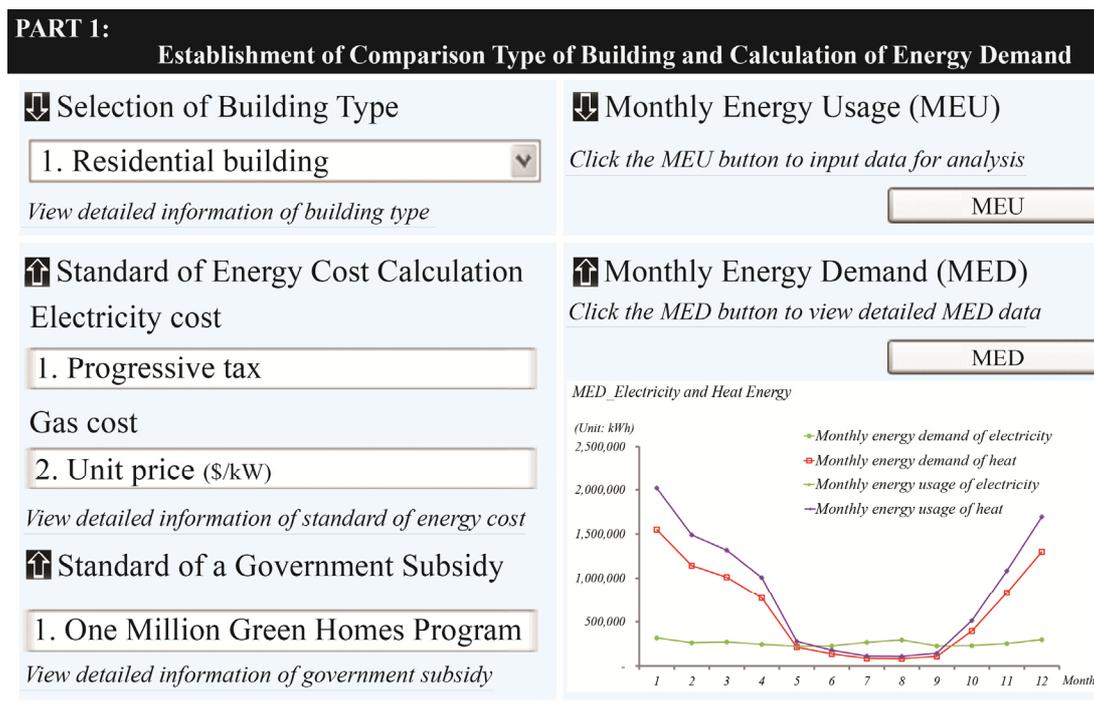


Table 1. Overview of Target buildings.

Category	Multi-family housing complex	Multi-use office complex
Location	Seoul	Seoul
Type	Residential	Non-residential
Heating system	Centralized	Centralized
Government subsidy	Yes (technically) No (practically)	Yes (technically) No (practically)
Progressive tax	Yes	No
Occupants of the building	Residents	Commuters/Students
Hours of use	AM 6–8/PM 7–12 (7 h)	AM 8–PM 8 (12 h)
Major energy consumption	Elec > Gas	Elec >> Gas
Amount of electricity per year (TOE)	1,885.35	4,822.08
Amount of Gas per year (TOE)	842.87	534.17
Total amount of Energy (TOE)	2,728.22	5,356.25
Total Energy Cost (US\$)	1,414,634	1,382,248

3.1.2. Calculation of the Monthly Energy Demand of a Given Building

The actual energy consumption data of the target buildings should be collected to conduct the energy demand analysis. These energy consumption data were collected from the corresponding energy service providers (*i.e.*, Korea Electricity Power Corporation and Korea Gas Corporation).

First, in the case of the electricity energy, the monthly energy usage of electricity (MEU_E) means the monthly energy demand of electricity (MED_E) (refer to Equation (1)) [69]. Second, in the case of the heat energy, the supplied gas is converted into heat energy through heat source equipment (*i.e.*, a boiler), and therefore loss factors are generated in the process of calculating the monthly energy

demand for heat energy (MED_H) from the monthly energy usage of gas (MEU_G). The operation standard of the *Building Energy Rating System* in South Korea classifies the loss factors into two types: (i) the pipe-loss coefficient and (ii) the boiler load loss coefficient [70]. By considering these two types of the loss factors and the existing boiler efficiency, the monthly energy demand for heat energy (MED_H) of the target building can be calculated as follows (refer to Equation (2)):

$$MED_E = MEU_E \quad (1)$$

$$MED_H = MEU_G \times \Omega \times \Delta \times \delta \quad (2)$$

where MED_E (kWh) is the monthly energy demand of electricity; MED_H (kWh) is the monthly energy demand of heat; MEU_E (kWh) is the monthly energy usage of electricity; MEU_H (kWh) is the monthly energy usage of heat; Ω is the pipe-loss coefficient (0.95); Δ is the boiler load-loss coefficient (0.95); and δ is the boiler efficiency (0.85).

3.2. Part 2: Establishment of the Fuel Cell System Implementation Strategies

The implementation strategies of the fuel cell system should be established by considering the following two critical factors: (i) the operating scheme of the fuel cell system and (ii) the operating size of the fuel cell system [58–61,65–68].

First, depending on the operating scheme of the fuel cell system, that is, as to which energy would be focused in the implementation process of the fuel cell system for a given building, the economic and environmental effects may differ drastically. The operating scheme of a fuel cell system can be generally divided into three categories: (i) the full power capacity output (FPCO); (ii) the power load following (PLF); and (iii) the heating load following (HLF) [58–61].

Second, the operating size of the fuel cell system is directly related to the energy supply of the fuel cell system. However, even if the operating size of the fuel cell system increases, the energy supply of the fuel cell system may be limited depending on its operating scheme. In other words, considering only the operating size of the fuel cell system based on the monthly energy demand of a given building, may lead to an excessive capacity design [65–68]. Therefore, to maximize the implementation effect of the fuel cell system and to accurately evaluate its effect, the two critical factors (*i.e.*, the operating scheme and the operating size of the fuel cell system) should be considered simultaneously. Since the MCFC type can produce 100 kW as the minimum unit, multiples of 100 kW can be used as the operating size of the fuel cell system [36,42,43]. The developed model sets the capacity at 100 kW, and three operating schemes of the fuel cell system can be selected to establish various implementation strategies (refer to Figure 2).

3.3. Part 3: Analysis of Energy Demand and Supply by Implementation Strategies

The monthly energy demand and supply can be analyzed based on the energy demand of a given building (refer to Section 3.1.2) and the energy supply of the fuel cell system. The equations for the monthly fuel cell system energy supply of electricity ($MFES_E$) and the monthly fuel cell system energy supply of heat energy ($MFES_H$) (refer to Equations (3) and (4)) are as follows:

$$MFES_E = MFU_G \times 3600 / H_R \quad (3)$$

$$MFES_H = HRE \times (MFU_G - MFES_E) / 100 \tag{4}$$

where $MFES_E$ (kWh) is the monthly fuel cell system energy supply of electricity; MFU_G (kWh) is the monthly fuel (gas) used in a fuel cell system; H_R (kJ/kWh) is the heat rate which is the amount of energy input (kJ) from the fuel required to generate 1 kWh of electricity; 3600 is the conversion factor (kJ/kWh) between kJ and kWh; $MFES_H$ (kWh) is the monthly fuel cell system energy supply of heat; and HRE (%) is the heat recovery efficiency which is the recovery ratio of waste heat in the electricity generation process. $MFES_E$ (kWh) can be calculated based on H_R (kJ/kWh) and MFU_G (kWh). Then, $MFES_H$ (kWh) can be deducted by multiplying HRE (%) and the amount of waste heat ($MFU_G - MFES_E$, (kWh)).

Using the aforementioned equations [refer to Equation (3) and (4)], the energy supply equations for a fuel cell system using the implementation strategies were established (refer to Table A1). These equations show that the energy supply of a fuel cell system is affected by the following three factors: (i) the energy demand of a given building, (ii) the operating scheme of the fuel cell system, and (iii) the operating size of the fuel cell system (refer to Table A1). Commercial programs such as *RETScreen* can calculate only the yearly energy generation of the fuel cell system, and thus, they cannot accurately analyze the energy demand and supply [71]. To address this limitation, this study developed a model that can calculate the monthly energy supply of the fuel cell system by considering the three key factors (*i.e.*, the energy demand of a given building, the operating scheme of the fuel cell system, and the operating size of the fuel cell system) (Figure 3 and Table A1).

Figure 2. Graphical user interface of Part 2.

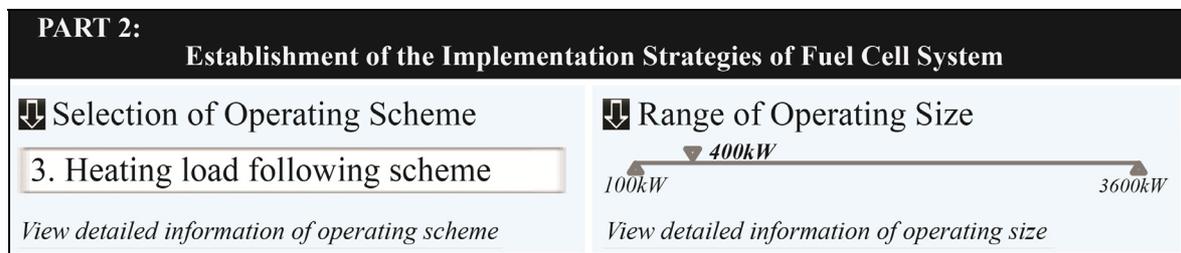
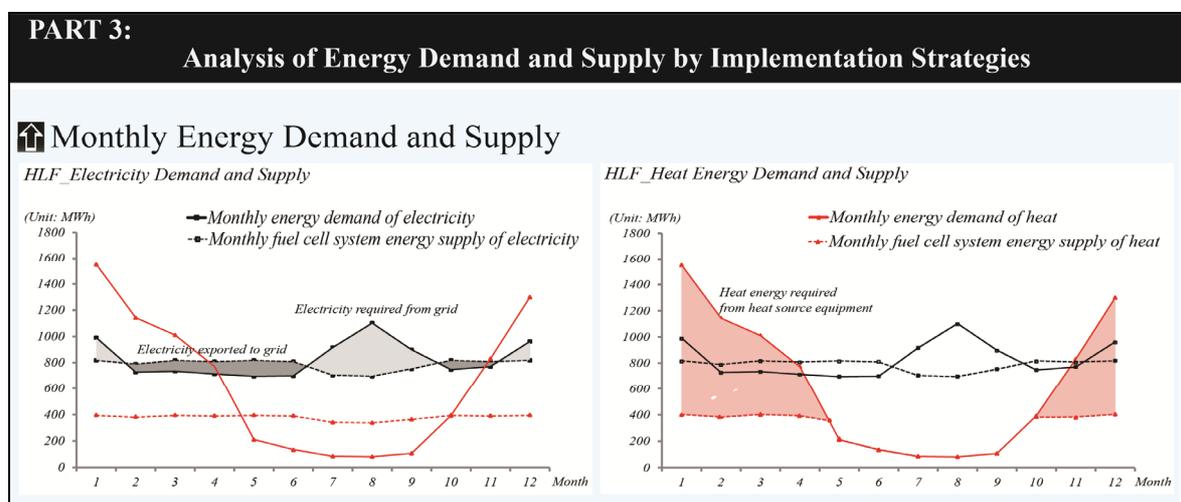


Figure 3. Graphical user interface of Part 3.



By comparing the monthly energy demand of a given building and monthly energy supply of fuel cell system, the important information needed for the LCC and LCCO₂ analysis (*i.e.*, electricity exported to grid, electricity required from grid, heat energy required from the heat source equipment, and heat energy wasted) can be deducted (refer to Figure 3). In this study, on-grid application of the fuel cell system in a building was considered. Therefore, it is assumed that the surplus electricity is sold to the grid and the surplus heat energy is dumped without any storage mechanism. In the case of the FPCO scheme, the energy supply of the fuel cell system can exceed the demand for both electricity and heat energy of a given building. Surplus electricity can be exported to the grid, however, surplus heat energy cannot be reused. On the other hand, in the case of a PLF scheme, the electricity supply of fuel cell system cannot exceed the electricity demand of a given building, therefore, electricity cannot be exported to the grid. In the case of HLF, the heat energy supply of the fuel cell system cannot exceed the heat energy demand of a given building. Therefore, heat energy cannot be wasted (refer to Figure 3).

3.4. Part 4: LCC and LCCO₂ Analysis

Based on the analysis of the energy demand and supply by the implementation strategies in Section 3.3, this study could conduct economic and environmental assessments based on the implementation strategies of the fuel cell system for a given building. To do this, LCC and LCCO₂ were used. To select the optimal implementation strategy, the economic and environmental values should be expressed as one index. To do this, the amount of LCCO₂ emissions reduction was converted into an economic value. Table A2 shows the boundary conditions of the LCC and LCCO₂ analysis (refer to Figure 4).

Figure 4. Graphical user interface of Part 4.

PART 4:
LCC and LCCO₂ Analysis

⌵ Boundary Condition of LCC and LCCO₂

Selection of analysis approach

1. Net present value

Input the realistic discount rate

Interest	3.30%
Electricity	0.66%
Gas	0.11%
KCERs	2.66%

Input the analysis period 20 years

Input the starting point of analysis 2013

Significant cost of ownership

[View detailed information of boundary condition of LCC and LCCO₂](#)

⌵ Input the Fuel Cell System Cost Information (FCSCI)

Click the FCSCI button to input data for analysis

First, two main indicators were selected for the LCC and LCCO₂ analysis: (i) NPV and (ii) BEP. If $NPV \geq 0$, the project is feasible and the BEP is achieved. The interest rate was calculated by considering the nominal interest and the inflation rate. In addition, the analysis period was set at 20 years by considering the service life of a fuel cell system [36,72–74].

Second, the significant costs of ownership, such as the initial construction cost and the operation and maintenance costs, should be established. According to the *Certification for New and Renewable Energy Facilities System*, government subsidies will cover up to 67% of the initial investment cost of the fuel cell system [75]. For the environmental assessment, the CO₂ emissions reduction was converted into an economic value using the coefficient of the *Korea Certified Emission Reduction* (KCERs (\$10.8/tCO₂-eq.)). Furthermore, the surplus electricity produced by the fuel cell system, which can be exported to the grid through the Korea Electric Power Corporation, can be converted into an economic benefit by multiplying with the system marginal price (SMP, \$0.15/kWh), which is the price of the last block of electric energy dispatched to meet the physical requirements of the system in South Korea, excluding exports and imports. The electricity market price is applied in the transactions involving electricity generated from non-fossil fuels [69,75].

3.5. Graphical User Interface of the Developed Model

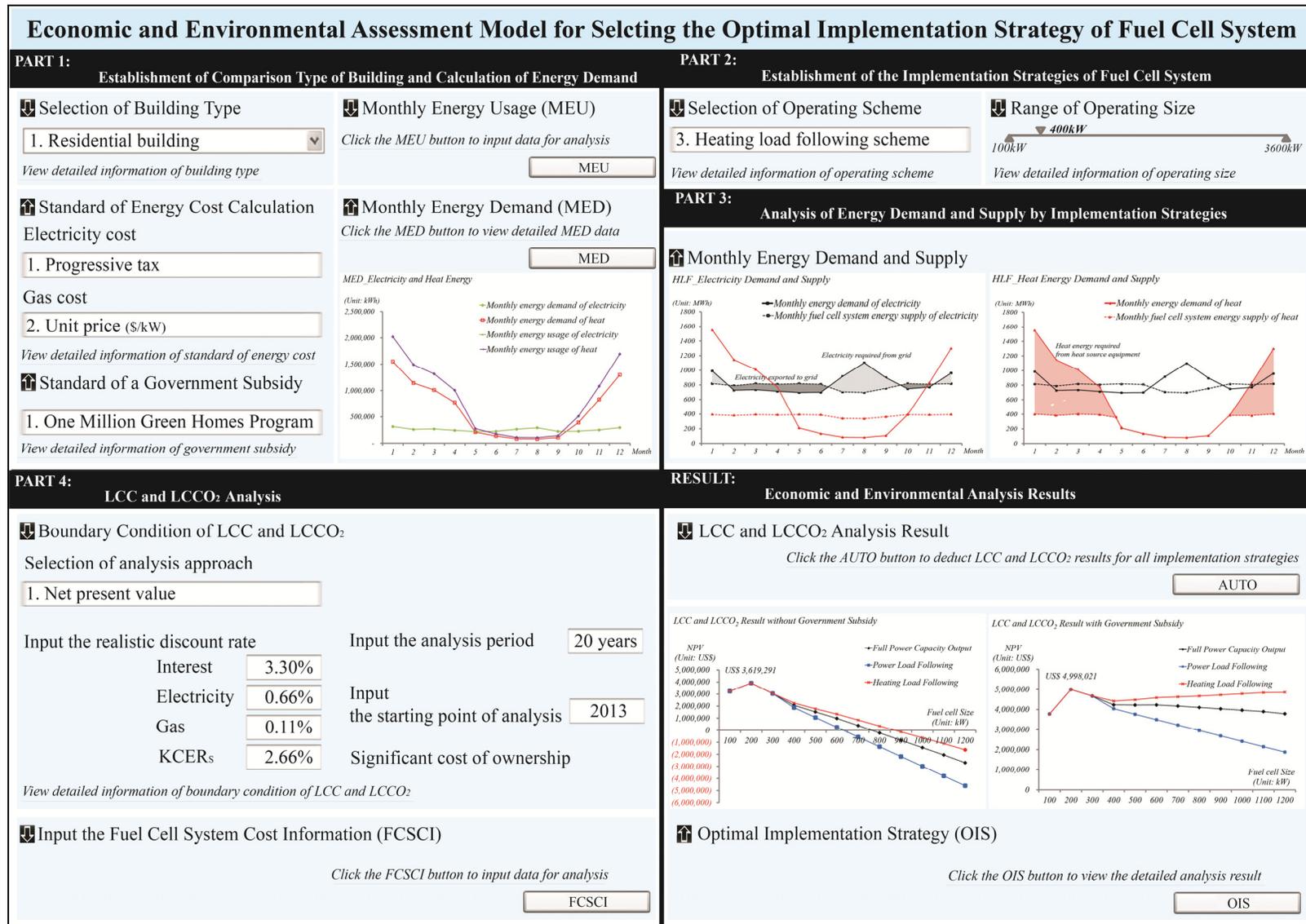
An essential focus on this study is to advance an economic and environmental assessment model; that is to select the optimal implementation strategy of the fuel cell system. Since there were various factors, equations, and a series of processes (refer to Section 3, “*Materials and methods*”), this study developed a graphical user interface by integrating the information from Part 1 to Part 4. A Microsoft-Excel-based VBA was used to develop the aforementioned model (refer to Figure 5). The following factors were considered in the model development process:

- The simplicity of the input variables, to improve user convenience;
- The automatization of the developed model, to shorten the execution time;
- Visualization of the analysis results, to help the final decision-maker recognize the optimal implementation strategy of the fuel cell system easily and clearly; and
- The expandability of the developed model, to enable the final decision-maker to apply the developed model to any other country or any other type of building.

This model consists of four parts (Part 1 to Part 4) and analysis results. Their detailed information is as follows:

- Part 1: the user can select building type. Then, the energy cost calculation and government subsidy standards will be determined automatically according to the building type. The users need to input the monthly energy usage information to deduce the monthly energy demand of a given building (refer to Equation (1) and (2));
- Part 2: the users can establish an implementation strategy by selecting the operating scheme and operating size of the fuel cell system. The monthly energy supply of the fuel cell system will be calculated and automatically saved on the database server (refer to Table A1). In the model, the user can choose default or referenced specifics of the fuel cell system (*i.e.*, heat rate and heat recovery efficiency of MCFC) (refer to Table A3);

Figure 5. Graphical user interface of the developed model.



- Part 3: the comparison results between monthly energy demand of a given building (from Part 1) and monthly energy supply of the fuel cell system (from Part 2) will be presented in Part 3. And detailed information (*i.e.*, electricity exported to grid, electricity required from grid, heat energy required from the heat source equipment, and heat energy wasted) for LCC and LCCO₂ analysis will be automatically saved on the database server;
- Part 4: the users can input detailed indices for LCC and LCCO₂ analysis (*i.e.*, realistic discount rate, the analysis period, and the starting point of analysis). The user can also use the recommended value of this model; and
- Result: the users can conduct the LCC and LCCO₂ analysis in terms of NPV and BEP of a selected implementation strategy. This model provides an “Auto” function which draws the optimal implementation strategy in terms of LCC and LCCO₂ by calculating all of the possible implementation strategies for a given set of conditions.

4. Results and Discussion

The developed model was applied to the two types of buildings (*i.e.*, residential building and non-residential building), which considered the following two type of building energy policies: (i) the standard of energy cost calculation; and (ii) the standard of a government subsidy. This study established the optimal implementation strategy of the fuel cell system in terms of the LCC and LCCO₂ as follows:

4.1. “O” Multi-family Housing Complex with Progressive Tax

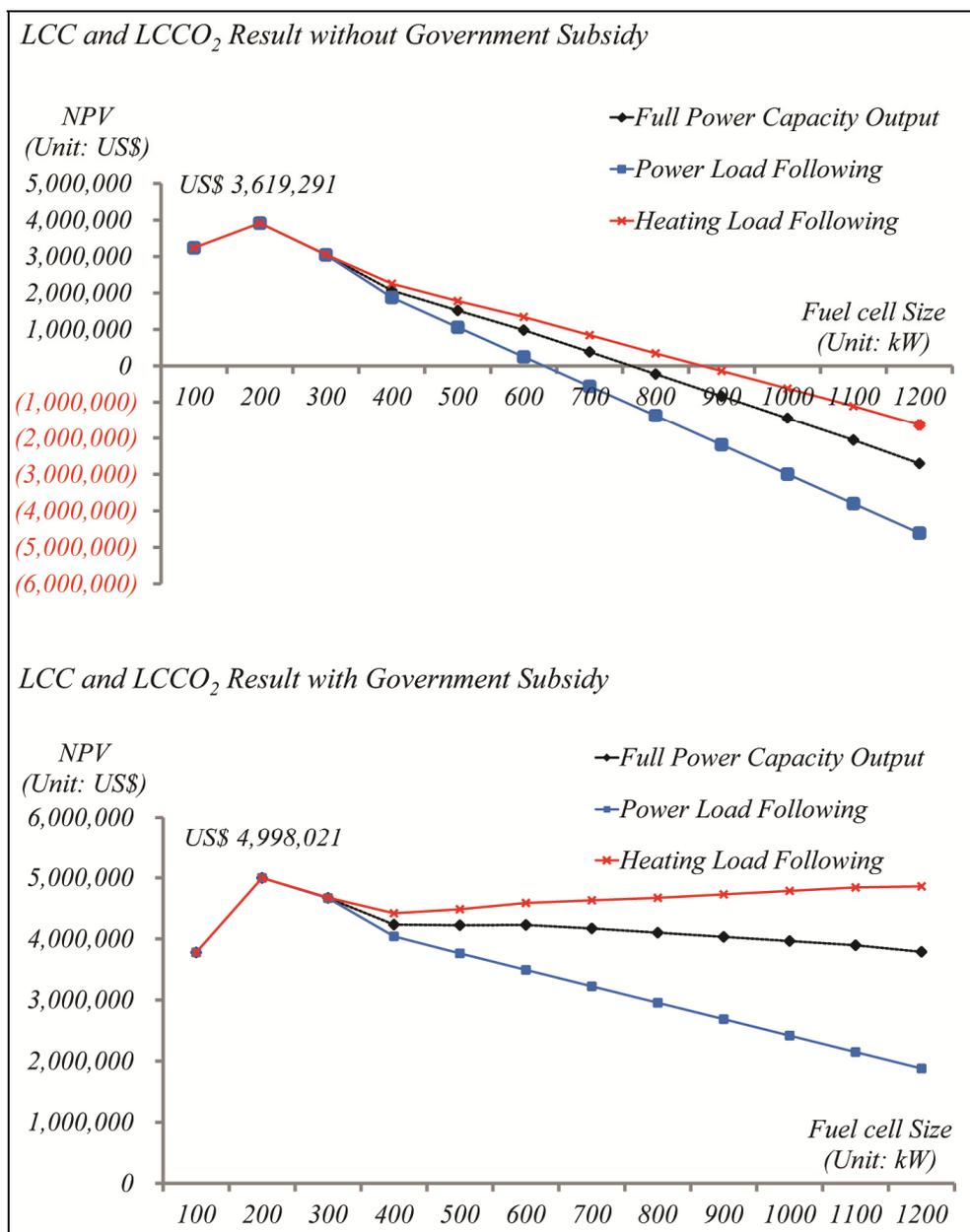
As for multi-family housing complex, IS_HLF_200 kW (where the operating scheme was HLF and the operating size was 200 kW) was determined to be the optimal implementation strategy for the fuel cell system. The results if the government subsidy was either considered or not were as follows:

First, if the government subsidy was not considered, 19.5% of the life cycle energy cost could be saved. NPV₂₀ and BEP were determined as US\$3,619,291 and three years, respectively. This is because although the gas energy cost increased by 23.5%, 78.8% of the electricity energy cost could be saved based on the effect of the progressive tax that is applied to residential buildings (refer to Figure 6).

- Operating scheme: In the case of “O” multi-family housing complex, the HLF scheme was superior to the other operating schemes. It was shown to be the most cost-effective because it allowed exported-to-the-grid sales in winter and it did not produce surplus heat energy in summer. On the other hand, in the case of the FPCO scheme, while its exported-to-the-grid sales were highest, its monthly fuel used in a fuel cell system (MFU_G) and its surplus heat energy, which cannot be recycled in summer, were too high. Furthermore, in the case of the PLF scheme, there was no exported-to-the-grid sales due to the properties of its operating scheme; and like the FPCO scheme, it produced large surplus heat energy in summer.
- Operating size: The optimal operating size of the fuel cell system was found to be IS_HLF_200 kW. If the energy surplus of the fuel cell system is higher than the energy demand of a given building (more than 300 kW), the FPCO scheme could not recover the increase in the initial construction cost due to the increase of its capacity, as the SMP is low and the gas cost is high. On the other hand,

the PLF scheme and the HLF scheme did not offer additional economic benefits due to the properties of their operating schemes. In other words, as the operating size of the fuel cell system increases, it cannot produce surplus electricity or heat energy but the initial construction cost and the operating and maintenance costs do increase. Therefore, the optimal operating size of the fuel cell system was shown to be IS_HLF_200 kW, at which the energy supply of the fuel cell system came closest to the energy demand of a given building.

Figure 6. LCC and LCCO₂ result of “O” Multi-family Housing Complex with Progressive Tax.



Second, if the government subsidy was considered, IS_HLF_200 kW was also shown to be the optimal scenario. In this case, NPV₂₀, its saving ratio, and BEP were determined to have been US\$4,998,021, 19.5%, and one year (refer to Figure 6). These results were analyzed to have the same context as the first case discussed above, where the NPV was increased and the BEP was decreased due to the decrease in the initial construction cost.

4.2. “Y” Multi-use Office Complex without Progressive Tax

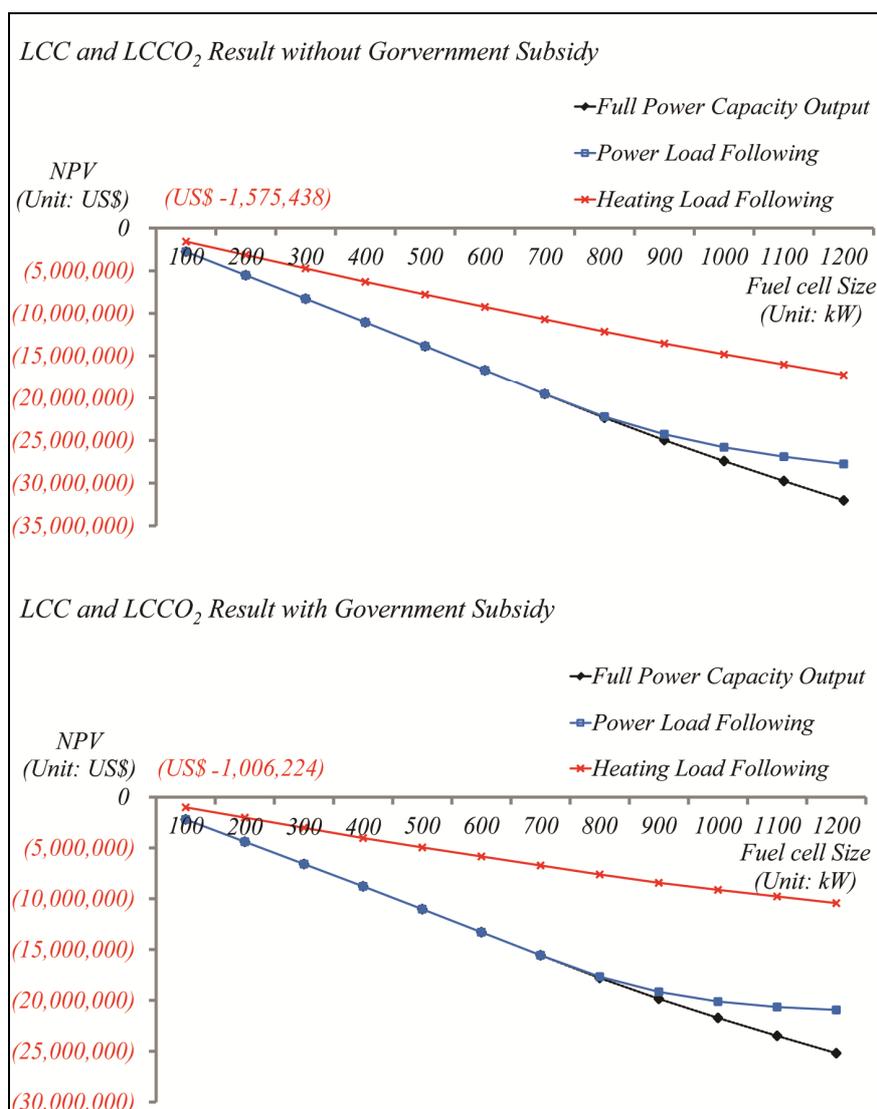
As for multi-use office complex, IS_HLF_100 kW (where the operating scheme was HLF and the operating size was 100 kW) was determined to be the optimal implementation strategy of the fuel cell system. The results if the government subsidy was either considered or not were as follows:

First, if the government subsidy was not considered, 15.4% of the life cycle energy cost could be saved. However, NPV₂₀ was determined as −US\$1,575,438, which was a negative value (refer to Figure 7).

- Operating scheme: In the case of “Y” multi-use office complex, the HLF scheme was superior to the other operating schemes in terms of LCC and LCCO₂. This result was analyzed to have the same context as that of “O” multi-family housing complex.
- Operating size: The optimal operating size of the fuel cell system was found to be IS_HLF_100 kW. Although “Y” multi-use office complex was almost similar to “O” multi-family housing complex in terms of the yearly energy cost, the primary energy usage of “Y” multi-use office complex was 96.4% higher than that of “O” multi-family housing complex. Nevertheless, no implementation strategy of the fuel cell system satisfied NPV₂₀ > 0.
- In summary, the analysis results showed that considering only the energy demand of a given building in implementing the fuel cell system would not achieve an economic effect. Despite the larger amount of energy consumption in “Y” multi-use office complex, the LCC and LCCO₂ results of “O” multi-family housing complex was superior to that of “Y” multi-use office complex, which depended on the progressive tax. In other words, “Y” multi-use office complex, as a non-residential building, is not affected by the progressive tax. This results means that the benefits from the fuel cell system (*i.e.*, the energy saving effect) do not cancel out the initial construction cost, the operating and maintenance cost, and the gas cost of the fuel cell system.

Second, if the government subsidy was considered, as the first case discussed above where it was not considered, NPV₂₀ was determined as a negative value (−US\$769,347). This result means that even after 100% of the financial support for the initial construction cost from a government subsidy, the fuel cell system would not achieve an economic effect. This was attributed to the relatively low electricity cost and SMP, and the relatively high gas energy cost. In other words, the following factors should be considered to achieve an economic benefit from the implementation of the fuel cell system for a non-residential building that is not affected by the progressive tax: (i) the SMP should be increased; (ii) the gas energy cost should be decreased; and (iii) the government subsidy should be improved.

Figure 7. LCC and LCCO₂ result of “Y” Multi-use Office Complex without Progressive Tax.



5. Conclusions

This study aimed to develop an economic and environmental assessment model for selecting the optimal implementation strategy of a fuel cell system, focusing on building energy policy. The developed model was applied to two types of buildings (*i.e.*, residential building and non-residential building), which represented two types of building energy policy: (i) the standard of energy cost calculation; and (ii) the standard of a government subsidy. This study established the optimal implementation strategy of the fuel cell system in terms of the LCC and LCCO₂ as follows:

- Residential building: Since the progressive tax is applied to this type of building, the more electricity energy was used, the more significantly the fuel cell system affected the electricity energy savings. As for multi-family housing complex, IS_HLF_200kW was determined to be the optimal implementation strategy. First, without government subsidy, 19.5% of the life cycle energy cost was saved. NPV₂₀ and BEP were determined as US\$3,619,291 and three years, respectively. Next, with government subsidy, NPV₂₀ and BEP were determined as US\$4,998,021 and one year, respectively, due to the decrease in the initial construction cost.

- Non-residential building: Since the progressive tax is not applied to this type of building, the fuel cell system affected the electricity energy savings significantly less compared to the residential building. In other words, the increase in the gas energy cost of the fuel cell system was larger than the electricity energy cost savings with the implementation of the fuel cell system. In the case of “Y” multi-use office complex, even after 100% of the financial support for the initial construction cost from a government subsidy, there was no life cycle saving effect. That is, none of the implementation strategies was able to make the fuel cell system feasible. Therefore, to actively promote the implementation of the fuel cell system in non-residential building, only using an improvement of the government subsidy would not be meaningful. Rather, it is necessary to adjust the energy cost, such as an increase in the SMP, a decrease in the gas price, and to apply the progressive tax to non-residential building.

The developed model can be used for establishing the optimal implementation strategy of the fuel cell system, which can consider not only the energy demand of a given building, but also the building energy policy. In addition, the developed model could be applied to any other country or any other type of building. It is expected that the practicality of the developed model can be improved by the following future studies: (i) this study set bounds to MCFC, as a fuel cell type, which was the suitable for large scale buildings; if the combined implementation of the fuel cell system can be established, the developed model could be extended further; (ii) if the operating scheme can be established based on the monthly energy demand, the developed model will be more reliable; (iii) this model was developed on the monthly basis. If the energy usage pattern of a given building can be reflected on the hourly basis, the model's accuracy will be more improved; and (iv) this study considered on-grid application of the fuel cell system in a building. If the energy storage mechanism can be established, the developed model can deal with off-grid application of the fuel cell system in a building.

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Author Contributions

All authors read and approved the manuscript. All authors contributed to this work, discussed the results and implications and commented on the manuscript at all stages. Taehoon Hong gave precious advice on the establishment of framework as well as design model. Daeho Kim made model with co-authors and helped understand the fuel cell system more thoroughly. Jimin Kim discussed the main idea behind the work and reviewed and revised the manuscript. Choongwan Koo led the development of the paper and conducted the LCC and LCCO₂ analysis.

Appendix

Table A1. Monthly fuel-cell system energy supply equation according to operating scheme.

Operating scheme	Equations
Full power capacity output (FPCO)	$MFES_E^{FPCO} = \text{operating size of a fuel cell system} \times \text{total operating time}$ $MFES_H^{FPCO} = \{HRE \times [MFU_G - (MFU_G \times 3600 / H_R)]\} / 100$
Power load Following (PLF)	$MFES_E^{PLF} = MED_E$ $Max_of_MFES_E^{PLF} = MFES_E^{FPCO}$ $MFES_H^{PLF} = HRE \times (MFES_E^{PLF} \times H_R / 3600 - MFES_E^{PLF}) / 100$
Heating load Following (HLF)	$MFES_H^{HLF} = MED_H$ $Max_of_MFES_H^{HLF} = MFES_H^{FPCO}$ $MFES_E^{HLF} = MFES_H^{HLF} / HRE \times 360000 / H_R / (1 - 3600 / H_R)$

Note: $MFES_E^{FPCO}$ is the monthly fuel cell system energy supply of electricity in FPCO scheme; $MFES_H^{FPCO}$ is the monthly fuel cell system energy supply of heat in FPCO scheme; MFU_G is the monthly fuel (gas) used in a fuel cell system; H_R is the heat rate; and HRE is the heat recovery efficiency; $MFES_E^{PLF}$ is the monthly fuel cell system energy supply of electricity in PLF scheme; MED_E is the monthly energy demand of electricity; $MFES_H^{PLF}$ is the monthly fuel cell system energy supply of heat in PLF scheme; $MFES_H^{HLF}$ is the monthly fuel cell system energy supply of heat in HLF scheme; MED_H is the monthly energy demand of heat; $MFES_E^{HLF}$ is the monthly fuel cell system energy supply of electricity in HLF scheme.

Table A2. Boundary condition of LCC and LCCO₂.

Classification	Detailed classification	Detailed description	
	Analysis approach	Present worth method (NPV ₂₀ , BEP)	
Realistic discount rate	Interest	3.30%	
	Electricity	0.66%	
	Gas	0.11%	
	KCER _s	2.66%	
	Analysis period	20 years	
	Starting point of analysis	2013	
Significant cost of ownership	Initial construction cost	Initial investment cost	
	Initial benefit	Government subsidy (67%)	
	Operation & maintenance cost	Replacement/repair cost	
		Energy consumption cost	
	Operation & maintenance benefit	Progressive tax	
		Gas savings, electricity savings	
Benefit from SMP			
		Benefit from KCER _s	

Table A3. Specifics of four types of a fuel cell system.

TYPE	PEMFC ¹	PAFC ²	MCFC ³	SOFC ⁴
	1st generation	2nd generation		3th generation
Development	Commercialization phase		Verification phase	
Application range	Car-Home	Building	Building-Plant	Home-Building
Size (kW)	1 kW	100 kW~	100 kW~	1 kW~
Heat rate (kJ/kWh)	10,286	8,571	7,660	6,545
Heat recovery efficiency (%)	50%	48%	43%	35%
Operating temperature (°C)	25~80	200	650	800
Initial cost (\$/kW)	5,712	4,284	4,284	7,235
O & M	1.5%/year	30%/5 year	30%/5 year	30%/5 year
External reformers	necessary	necessary	unnecessary	unnecessary
Stack	Platinum	Platinum	Perovskites	Nickel
	High price	Low price		Low price
Life duration(year)	10	20	20	20

Note: ¹ PEMFC stands for proton exchange membrane fuel cell; ² PAFC stands for phosphoric acid fuel cell; ³ MCFC stands for molten carbonate fuel cell; and ⁴ SOFC stands for solid oxide fuel cell.

Nomenclature

Abbreviations	Detailed explanation
<i>IS_HLF_200 kW</i>	Implementation strategy (IS) with the operating scheme of Heating Load Following (HLF) and the operating size of 200 kW
<i>IS_HLF_100 kW</i>	Implementation strategy (IS) with the operating scheme of Heating Load Following (HLF) and the operating size of 100 kW
<i>MEU_E</i>	Monthly Energy Usage of Electricity (kWh)
<i>MEU_G</i>	Monthly Energy Usage of Gas (kWh)
<i>MED_E</i>	Monthly Energy Demand of Electricity (kWh)
<i>MED_H</i>	Monthly Energy Demand of Heat (kWh)
<i>MFES_E</i>	Monthly fuel cell system Energy Supply of Electricity (kWh)
<i>MFES_H</i>	Monthly fuel cell system Energy Supply of Heat (kWh)
<i>MFU_G</i>	Monthly Fuel(Gas) Used in a fuel cell system (kWh)
<i>MES_E</i>	Monthly Energy Saving of Electricity (kWh)
<i>MES_G</i>	Monthly Energy Saving of Gas (kWh)
<i>H_R</i>	Heat Rate (kJ/kWh)
<i>HRE</i>	Heat Recovery Efficiency (%)
Ω (Greek letter)	Pipe-loss coefficient
Δ (Greek letter)	Boiler load-loss coefficient
δ (Greek letter)	Boiler efficiency

Conflicts of Interest

The authors declare no conflict of interest.

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