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Article

A Process for the Implementation of New Renewable Energy Systems in a Building by Considering Environmental and Economic Effect

Chan-Joong Kim [1], Taehoon Hong [2,†,*], Jimin Kim [2,†], Daeho Kim [2,†] and Dong-yeon Seo [3,†]

[1] Parsons Brinckerhoff, Seoul 135-763, Korea; E-Mail: kim.cj@pbworld.com

[2] Department of Architectural Engineering, Yonsei University, Seoul 120-749, Korea; E-Mails: cookie6249@yonsei.ac.kr (J.K.); sternally@naver.com (D.K.)

[3] Division of Architecture & Urban Design, Incheon National University, Incheon 406-772, Korea; E-Mail: seody@incheon.ac.kr

† These authors contributed equally to this work.

* Author to whom correspondence should be addressed; E-Mail: hong7@yonsei.ac.kr; Tel.: +82-2-2123-5788; Fax: +82-2-2248-0382.

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Abstract: The excessive use of fossil fuels has led to global warming and air pollution. To solve these problems, interest in new renewable energy system (NRE system) has increased in recent years. In particular, photovoltaic, solar thermal heating, fuel cell and ground source heating system are actively implemented for achieving the zero energy building. Since the initial investment cost of the NRE system is quite expensive, it is necessary to conduct a feasibility study from the life cycle perspective. Therefore, this study aimed to develop the process for the implementation of NRE system in a building for the optimal design. This study was conducted with four steps: (i) establishing the basic information for the system installation; (ii) selecting key factors affecting system performances; (iii) making possible alternatives of the system installation; and (iv) selecting optimal system by considering environmental and economic effect. The proposed process could enable the final decision-maker to easily and accurately determine the optimal design of the NRE systems from the economic and environmental efficiency in the early design phase. The process could also be applied to any other NRE system and could be extended to any other country in the global environment.

Keywords: new renewable energy; photovoltaic system; solar thermal energy system; fuel cell system; ground source heat pump system

1. Introduction

The story of the development and use of energy begins with the story of the human civilization. However, the fossil fuel deposits are limited and are expected to be depleted by this century. Furthermore, the increase in the considerable demand of energy caused by the economic boom of developing countries like China and India is worsening the imbalance between global energy supply and demand [1–5]. Besides the issue of energy supply and demand, the tremendous amount of fossil fuel usage has produced greenhouse gases (GHGs), and it has caused global warming around the world. To cope with these problems, in 1997, 180 countries signed the Kyoto protocol which is an international agreement linked to the United Nations Framework Convention on Climate Change, which commits its parties by setting internationally binding emission reduction target [6–10]. The UN, the US, and China also proposed the Emission Trading Scheme (ETS) as a solution to fight against climate changes, which is a method to trade GHG emission rights. Following this trend, South Korea has also established the GHGs emission trading market since January 2015 [11–16].

As the resources problems is becoming serious issue, new renewable energy systems (NRE system) are becoming more important [17–24]. In particular, as the construction industry depends on the energy-consuming industries, it will not be able to avoid the duty to reduce GHGs emission. Thus, for the transition towards an eco-friendly industry system, it is required to implement NRE system in buildings. The types of NRE micro-generation systems in South Korea include photovoltaic system (PV system), solar thermal energy system (STE system), fuel cell system (FC system), and ground source heat pump system (GSHP system) [25–29]. These systems can replace the existing boiler/chiller system by supplying thermal and electric energy required in a building [30–33]. Despite these environmental advantages, in South Korea, consumers are still hesitating about the implementation of these NRE micro-generation systems in the middle of the many uncertainties regarding the cost and efficiency of its use. In addition, there have been insufficient studies providing a comprehensive method of assessing the environmental and economic effects of each NRE system and executing life cycle CO_2 assessment based on such effects [34–40].

Therefore, this study provides the implementation processes of the NRE system including PV, STE, FC, GSHP systems in South Korea. This study was conducted in four steps: (i) establishing the basic information for the each system installation; (ii) selecting key factors affecting system performances; (iii) making possible alternatives of the system installation; and (iv) selecting optimal system by considering environmental and economic effects at the same time.

In this way, from the early design phase of a building where NRE system are to be implemented, NRE system standard design guideline can be proposed so that the issues related to the installation of NRE system can be accurately recognized and planned. Therefore, reasonable NRE system by considering environmental and economic effects can be implemented to the target building and the implementation of NRE system can be promoted.

2. Process for the Implementation of New Renewable Energy Systems in a Building

This study aims to develop the process for implementation of NRE system in a building, which can be used in the early design phase, through a four-step process.

- Step 1: Establishing the basic information database for each system installation. The study defines the region, the facility type, and the power supply system type to be implemented. In addition, the study collects the basic information about the central and local government's support systems and any regulations when NRE systems are to be implemented (*i.e.*, budget limit, area limit and size limit).
- Step 2: Selecting key factors affecting system performances. Based on the data collected from Step 1, the study selects key factors to the production of NRE system and establishes the database. In other words, the study establishes the information of regional factors, design factors, and key factors of each NRE system by the use of each energy source in the target building.
- Step 3: Making possible alternatives of the system installation. Based on the database established in Step 2, the study produces possible alternatives of the system installation. First, it establishes a process with which to analyze the energy source and energy profile of the target building, based on which it establishes the scenario per NRE and embodied the system design through simulations.
- Step 4: Selecting optimal system by considering environmental and economic effects. From the NRE system scenarios established in Step 3, the study establishes the optimal selection process based on the life cycle cost (LCC) and life cycle CO_2 ($LCCO_2$). First, through the simulation results, the study calculates the energy production per scenario and evaluates whether it achieved the target energy production for the target building. By performing the LCC and $LCCO_2$ of the scenarios selected above, the study selects the optimal NRE system implementation scenario.

2.1. Step 1: Establishing the Basic Information for the Each System Installation

Before installing NRE system, basic information for the system installation should be established. This basic information is categorized in Figure 1 and details are described below.

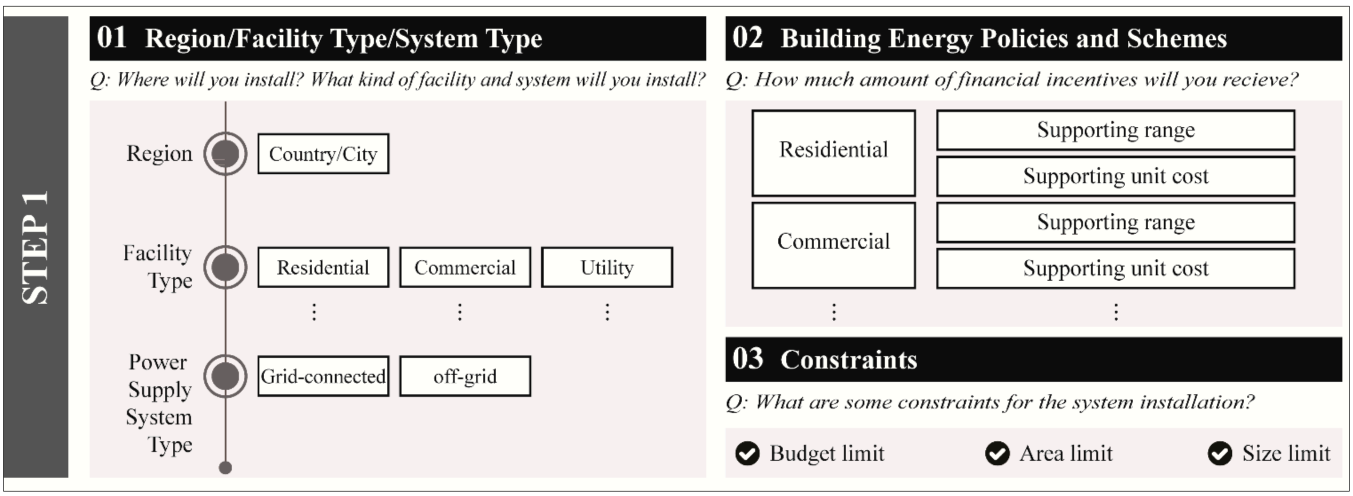

Figure 1. Establishing the basic information for the each system installation.

First, basic information regarding region, facility and power supply system should be determined. Depending on this information, there can be a significant difference in system performance and initial investment cost of the system.

Second, building energy policies and schemes (*i.e.*, the standard of the energy cost calculation and the standard of the government subsidy) are given in different regions, facilities, and power supply systems. Since each country or city has different building energy policies and schemes, it is crucial to know and understand what kind of energy policies and schemes are available in the region where a system will be installed. These kinds of energy policies and schemes are specifically divided into four categories [41–45]:

- Certification of NRE system: This certification scheme was designed to guarantee the quality of systems manufactured or imported to enhance user reliability. Certification of NRE system focuses on promoting the commercialization of NRE system (*i.e.*, PV, STE, FC, and GSHP system) in buildings;
- NRE system 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 1000 square meters, are obliged to use more than 10% of their total expected energy consumptions from installed NRE system;
- The standard of energy cost calculation: for the purpose of acceleration of NRE system deployment, the government provides a special fuel unit price (*i.e.*, a special unit price for gas only used for FC system) and a system marginal price (SMP) electricity market price applied in transactions involving electricity generated from non-fossil fuels, for NRE system users to participate in the utility market; and
- The standard of government subsidy: the government provides subsidies for NRE system users to promote NRE system 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 NRE systems, which already have been commercialized.

Among these building energy policies and schemes, the government subsidy and energy cost calculation standards should be given top priority in implementing NRE system to the buildings.

Finally, some constraints should be considered when planning and designing a NRE system. The two main constraints are the area and size limit: (i) the installation area limit should be enough for installing the desired system size; and (ii) to prevent oversizing of NRE system, the system size should not exceed the system size limit by considering the energy consumption of the target facility.

2.2. Step 2: Selecting Key Factors Affecting System Performances

In Step 2, there are some key factors that affect NRE system performances. These factors should be considered in advance in order to estimate system energy output and economic benefits under variable conditions. These key factors are categorized in Figure 2 and details are described below.

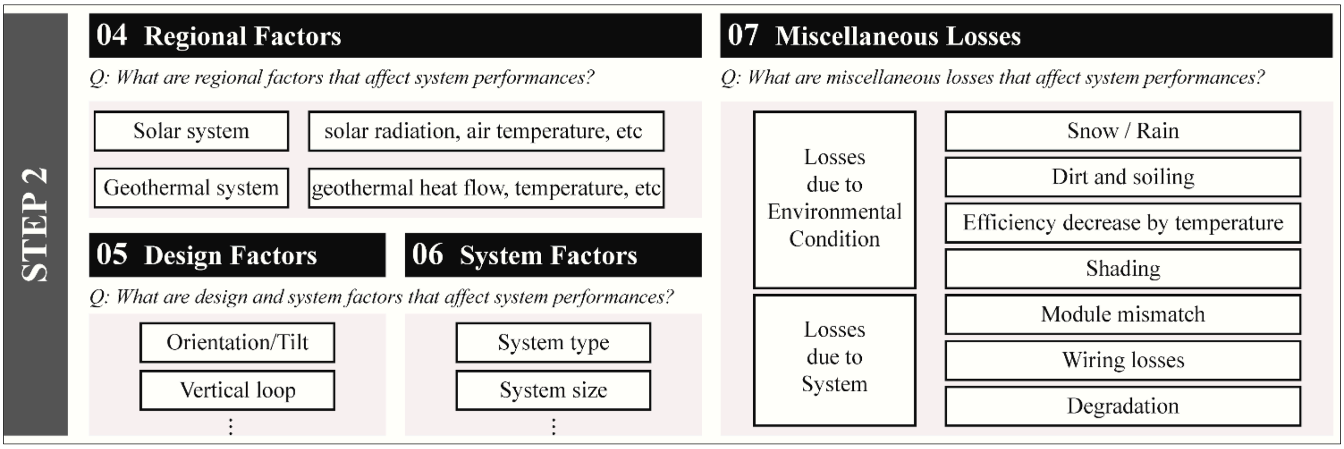

Figure 2. Selecting key factors affecting system performances.

2.2.1. Selecting Key Factors Affecting System Performances of the PV System

First, the energy output of a PV system is greatly affected by the regional factors such as the monthly average daily solar radiation (MADSR) and monthly average air temperature (MAAT). Since the MADSR and MAAT varies depending on the region, it is very crucial to determine these regional factors accurately and find out whether a certain region is appropriate for deploying the system.

Second, the energy output of a PV system is influenced by some design factors such as the orientation and tilt of the PV panel. The orientation and tilt of the PV panel determines how much energy that a PV system captures from the solar radiation [46]. In general, the PV system performs best when the panel is facing south (orientation: 0°), and worst when the panel is facing north (orientation: 180°). Between these two extremes, the optimal tilt of the panel is usually determined by the latitude of the target region [47].

Third, the energy output of a PV system is influenced by system factors like the types of PV panel and the inverter. The PV panel can mainly be categorized into two types by considering their materials and efficiencies: crystalline silicon and thin film [48]. The Crystalline silicon accounts for the majority of solar cell production with high efficiency. High efficiency module implies less PV systems' installation area in comparison with lower efficiency module having same capacity under Standard Test Conditions (STC) rating [49]. Meanwhile, DC to AC conversion efficiency varies depending on the inverter type and selecting the inverter with high efficiency can minimize the loss of electricity associated with conversion.

Finally, there can be miscellaneous losses of energy output due to some uncertainties. These miscellaneous losses should be considered before installing a PV system; otherwise actual system energy output could be far less than expected energy output. The typical reduction factors of each miscellaneous losses is as follows [50]: (i) snow: varies by region; (ii) dirt and soiling: 93%; (iii) efficiency decrease by temperature: 89%; (iv) shading: varies by case; (v) module mismatch: 98%; (vi) wiring losses: 97%; and (vii) degradation: the performance of the system degrades 0.8% every year (about 20% for 25 years).

2.2.2. Selecting Key Factors Affecting System Performances of the STE System

The study determines the applicability of the STE system. The key factor of STE system is very similar to that of the PV system, except that the modules of the PV system are used, instead of the solar thermal collectors of the STE system.

2.2.3. Selecting Key Factors Affecting System Performances of the FC System

According to the previous studies [51–58], which assessed the economic and environmental effects of the FC system, it was determined that there were complex correlations among the key factors affecting the energy performance of the FC system. As shown in Table 1, these key factors mostly consist of system factors.

Table 1. Key factors affecting system performances of fuel cell (FC) system.

Key Factor	Note
The type of the fuel cell system (ToFC)	PEMFC [1], PAFC [2], MCFC [3], SOFC [4]
The minimum operating rate (MOR)	%
The operating scheme (OSc)	FPCO [5], PLF [6], HLF [7]
The operating size (OSi)	kW

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; [4] SOFC stands for solid oxide fuel cell; [5] FPCO stands for the full power capacity output; [6] PLF stands for the power load following; and [7] HLF stands for the heating load following.

First, the type of the FC system (ToFC) is determined by the electrolyte used in the stack. According to ToFC, the operating temperature of the FC system is determined, and the energy performance differs based on two aspects: (i) the dynamic electricity/heat efficiency (DE); and (ii) electricity response rate (ERR). Firstly, since the heat required for maintaining the operating temperature differs by ToFC, the electricity/heat efficiency differs accordingly. Secondly, since different ToFC requires different amount of the operating temperature, the value of ERR also differs accordingly.

Second, to maximize the energy performance of the FC system, the operating temperature should be maintained, and therefore, the minimum operating rate (MOR) should be set. Since different ToFC requires different amount of the operating temperature, the MOR value also differs accordingly.

Third, the operating scheme (OSc) of the FC system can be divided into three types: (i) full power capacity output (FPCO); (ii) power load following (PLF); and (iii) heating load following (HLF). Firstly, FPCO, called not-following load, always operates at its maximum power regardless of the energy demand of a given building. Secondly, PLF operates at its maximum power within the range of the electricity demand of a given building. Lastly, HLF operates at its maximum power within the range of the heat energy demand of a given building.

Finally, although the operating size (OSi) increases, the amount of its energy generation cannot increase more than a certain level. Because the maximum amount of energy generation of the FC system can be determined according to its OSc. If energy demand of a given building is only considered the OSi not OSc, it can lead to the excessive initial investment cost of a FC system. Thus, the OSc and OSi should be considered simultaneously as key factors. Based on the key factors, the energy supply of the FC system can be calculated.

2.2.4. Selecting Key Factors Affecting System Performances of the GSHP System

First, the energy output of a GSHP system is greatly affected by the regional factors such as the earth temperature (ET), geothermal gradient (GG) and ground heat flux (GHF). Since the ET, GG and GHF varies depending on the region, it is very crucial to determine these regional factors accurately and find out whether a certain region is appropriate for deploying the system.

Second, the energy output of a GSHP system is influenced by some design factors such as the ground heat exchanger. The ground heat exchanger determines how much energy that a GSHP system captures from the ground source energy. In general, the ground heat exchanger performs according to depth of boring, the number of boring, grouting materials and chemical looping materials of pipe. The optimal key factors of the GSHP system are usually determined by the condition of the target region [59,60].

Third, the energy output of a GSHP system is influenced by system factors like the heat pump system connected to building HVAC system. It is important that the target production of the heating and cooling energy with constraints (*i.e.*, budget, area, size) is established through the application of the GSHP system to building HVAC system.

Finally, there can be miscellaneous losses of energy output due to some uncertainties: (i) the rock composition of the ground and the existence of underground water are checked; (ii) the existence of the underground utility, including water, sewage, electric installation, *et al.* Through the above-mentioned processes, the applicability of the GSHP system is determined.

2.3. Step 3: Making Possible Alternatives of the System Installation

In Step 3, by considering the key factors affecting NRE system performances, possible alternatives for selecting the optimal scenario can be established. Possible alternatives should satisfy three constraints: budget limit, area limit and size limit as mentioned in Step 1. With that, it is evaluated whether or not the energy production by each type of NRE systems exceeds target production. When possible alternatives are all set, annual system energy output can be estimated using NRE simulation program such as Energy plus, RETScreen or self-production program. Making possible alternatives are generated as Figure 3 and details are described below.

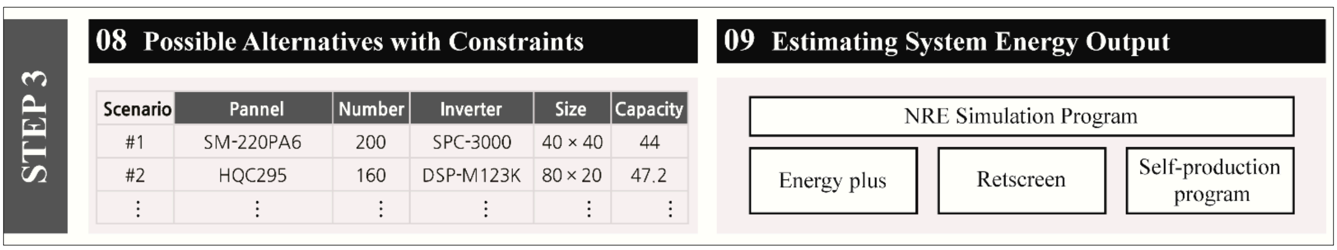

Figure 3. Making possible alternatives of the system installation.

2.3.1. Making Possible Alternatives of PV System

Possible alternatives of PV system can be established as follows [21]: (i) the target production of the electric energy with constraints (*i.e.*, budget, area, size) is established through the application of the PV system; (ii) the scenarios of the PV system are established by considering the number of installation of the PV system, its installation tilt, and the inverter capacity; and (iii) the energy production of the PV system is calculated by conducting energy simulation (the software program "Energy plus, RETScreen" and "Self-production program") based on the scenarios.

2.3.2. Making Possible Alternatives of STE System

Possible alternatives of STE system can be established as follows [21]: (i) the target production of the hot water supply energy with constraints (*i.e.*, budget, area, size) is established through the application of the STE system; (ii) the scenarios of the STE system are established by considering the number of installation of the STE system, its installation tilt, and the heat storage capacity; and (iii) the energy production of the STE system is calculated by conducting energy simulation (the software program "Energy plus" and "self-production program") based on the scenarios.

2.3.3. Making Possible Alternatives of FC System

Possible alternatives of FC system can be established as follows [61]: (i) the target production of the heating and cooling energy with constraints (*i.e.*, budget, area, size) is established through the application of the FC system; (ii) the scenarios of the FC system are established by considering the HVAC zone where the FC system is to be installed; and (iii) the energy production of the FC system is calculated by conducting energy simulation (the software program "RETScreen" and "Self-production program" based on the scenarios.

2.3.4. Making Possible Alternatives of GSHP System

Possible alternatives of GSHP system can be established as follows [21]: (i) the target production of the heating and cooling energy with constraints (*i.e.*, budget, area, size) is established through the application of the GSHP system; (ii) the scenarios of the GSHP system are established by considering the earth condition and HVAC zone where the GSHP system is to be installed; and (iii) the energy production of the GSHP system is calculated by conducting energy simulation (the software program "GLD" to ground heat exchanger and "Energy plus" to heat pump connected to building HVAC system) based on the scenarios.

2.3.5. Selection of the Scenario that Achieves Target Production with Constraints

The energy production by each type of NRE system is calculated using energy simulation. By evaluating achievement of the target production with constraints, the scenarios that satisfy the criteria are selected, and the LCC and $LCCO_2$ analysis are performed on these scenarios.

2.4. Step 4: Selecting Optimal System through Life Cycle Cost and Life Cycle CO_2 Analysis

In Step 4, the optimal system among possible alternatives established in the previous step can be selected through LCC and $LCCO_2$ analysis. This process is shown in Figure 4 and details are described below.

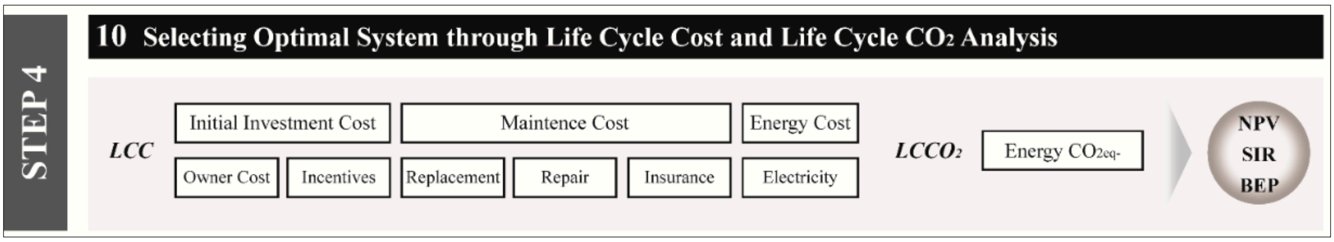

Figure 4. Selecting optimal system through life cycle cost and life cycle CO_2 analysis.

Basic assumptions for LCC and $LCCO_2$ analysis should be defined as follows: (i) analysis approach; (ii) analysis period; (iii) real discount rate by considering the inflation rate, the electricity and gas price growth rate, and the CO_2 emissions trading price growth rate; and (iv) significant cost of ownership (refer to Table A2).

First, the analysis approach: LCC and $LCCO_2$ analysis results can be presented in terms of net present value (NPV), saving to investment ratio (SIR), break-even point (BEP) and annual primary energy saving (APES). For instance, if NPV > 0, the project is feasible and the BEP is achieved.

Second, the analysis period: Generally, the analysis period for the LCC analysis can be established based on the standard service life, which is based on the building's structural type or type of NRE system. In this study, the analysis period was set by considering the service life of the NRE system [61–65].

Third, the real discount rate was calculated by considering the nominal interest and the inflation rate. In this study, reflecting the nominal interest rate and various inflation rates, the real discount rate was calculated. It can be used for converting various benefits and costs into present values.

Fourth, the significant costs of ownership, such as the initial construction cost and the operation and maintenance cost, should be established. Especially in this study, government subsidies, Korea Certified Emission Reduction (KCERs), and system marginal price (SMP) were considered as the significant costs of ownership. According to the Certification for NRE system, government subsidies were provided in the initial investment cost of the NRE system. For the environmental assessment, the CO_2 emissions reduction was converted into an economic value using the coefficient of the KCERs (\$10.8/tCO_2-eq.). Furthermore, the surplus electricity produced by the NRE 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 SMP (\$0.15/kWh). It 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.

3. Case Study for the Validation of the Proposed Process (Focused on Fuel Cell System)

To validate the process for the implementation of NRE system in the buildings, this study conducted a case study on "J" multi-family housing complex focused on FC system, since there are easily applicable to the buildings. By conducting a multilateral analysis on the results of the energy simulation, the energy generation (or substitution) effect was evaluated by applying the FC systems as NRE systems.

3.1. Step 1: Establishing the Basic Information for the FC System Installation

The compatibility analysis between the FC system and the existing system as well as the feasibility analysis for the implementation of the FC system can be performed by determining the basic information of the Facility and the FC system.

- Part 1: Region/facility/energy supply system type: This study aimed to develop process for the implementation of new renewable energy systems in a building. Therefore, "J" multi-family housing complex, which was closest to the average CO_2 emissions per unit area of all multi-family housing complex in Seoul, South Korea, was selected for the case study. Table 2 shows the basic information on the characteristics of "J" multi-family housing, as well as energy usage data.

Table 2. Overview of Target facility.

Category	Multi-Family Housing Complex
Location	Seoul
Type	Residential
Electricity system	On-grid
Heating system	Centralized
Government subsidy	Yes (technically) No (practically)
Progressive tax	Yes
Occupants of the building	457 Residents
Major energy consumption	Elec > Gas
Total amount of Energy (TOE)	1872
Total Energy Cost (US$)	$ 780,117

- Part 2: Energy policies and scheme: First, the FC system is a combined heat and power (CHP) system that can simultaneously produce electricity and heat energy. Thus, 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, as mentioned above, it is necessary to consider the type of building in calculating the building's energy cost. The information can be gathered from the electricity service providers of South Korea (*i.e.*, "Korea Electricity Power Corporation") and the information can be gathered from the gas service provider of South Korea (*i.e.*, "Korea Gas Corporation"). Second, the FC system has a higher initial construction cost per unit capacity than other NRE systems. Thus, government subsidies should be considered to ensure the economic feasibility of the FC 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 (refer to Table 3).

Table 3. The standard of the government subsidy.

Category	Target Facility	Application Range	Amount of Grant ($/kW)
One Million Green Homes	Seoul	<1 kW	31,246
Building Support Program	Residential	<20 kW	31,246

3.2. Step 2: Selecting Key Factors Affecting System Performances

The installation scope of the FC system is determined by the characteristics of the target building. Since the FC system is diverse in type (*i.e.*, PEMFC, PAFC, MCFC, and SOFC) and size (*i.e.*, 1 kWh, 3 kWh, 5 kWh, 20 kWh, and 100 kW), and therefore, it can be installed in a household or a complex scale. Table A1 shows the FC system types and sizes in accordance with the Installation scope of the FC system.

According to section 3.1, these key factors mostly consist of system factors: (i) The type of the FC system (ToFC); (ii) The minimum operating rate (MOR); (iii) The operating scheme (OSc); and (iv) The operating size (OSi). Based on the proposed key factors, energy supply calculation process can be developed and the energy performance of each scenario can be assessed.

3.3. Step 3: Making Possible Alternatives of the System Installation

As shown in Figure 5, the energy supply calculation process for making possible alternative scenarios of the FC system consists of 5 phases [66]: (i) calculation of the hourly operating rate (HOR); (ii) check for the MOR standard; (iii) check for the ERR standard; (iv) calculation of the electricity/heat efficiency on the hourly basis; and (v) calculation of the electricity/heat supply.

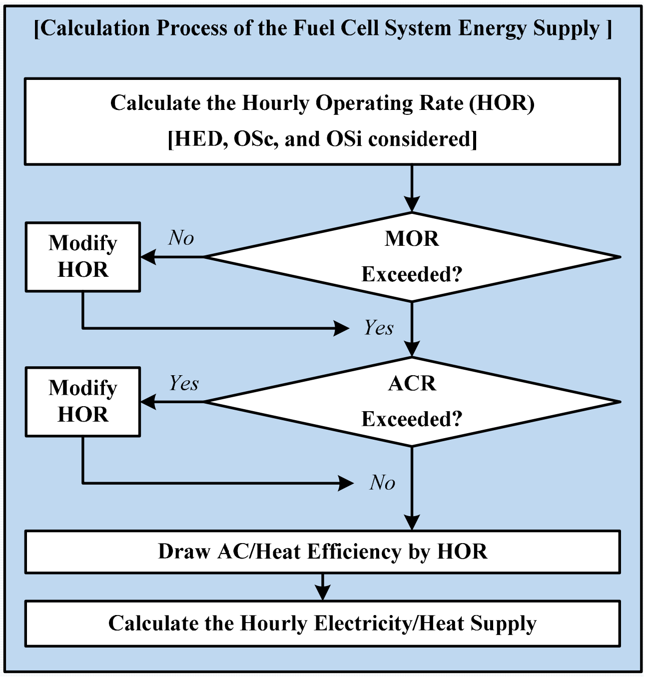

Figure 5. The calculation process of the fuel cell system energy supply.

- Phase 1: Calculation of the hourly operating rate (HOR): Above all things, the hourly operating rate of the FC system (HOR) should be calculated first in accordance with the OSc, the OSi, and the hourly energy demand of a given building (HED) (refer to Table 4). In the case of FPCO, the HOR should be always 100% (refer to Equations (1)–(2)). On the other hand, HOR should be followed based on the hourly electricity demand of a given building (HED_E) in PLF (refer to Equation (4)) and HOR should be followed based on the hourly heat energy demand of a given building (HED_H) in HLF (refer to Equation (6)).

Table 4. Equations for calculation of the hourly operating rate of the FC system.

Category	HED > OS_I	No.	HED < OS_I	No.
In the case of FPCO	$HOR_{FPCO} = 100\%$	(1)	$HOR_{FPCO} = 100\%$	(2)
In the case of PLF	$HOR_{PLF} = 100\%$	(3)	$HOR_{PLF} = HED_E / OS_I$	(4)
In the case of HLF	$HOR_{HLF} = 100\%$	(5)	$HOR_{HLF} = HED_H / OS_I \times (HE_{100\%} / EE_{100\%}) \times \Omega$	(6)

where, HOR_{FPCO} is the hourly operating rate of the FC system at full power capacity output scheme; HOR_{PLF} is the hourly operating rate of the FC system at power load following scheme; HOR_{HLF} is the hourly operating rate of the FC system at heat load following scheme; HED_E is the hourly energy demand of electricity of a given building; HED_H is the hourly energy demand of heat of a given building; $HE_{100\%}$ is the heat efficiency of the FC system at 100% operating rate; $EE_{100\%}$ is the electricity efficiency of the FC system at 100% operating rate; Ω is the NRE system pipe loss coefficient (0.95).

- Phase 2: Check for the MOR standard: the calculated HOR should observe the MOR standard as mentioned above. Therefore the HOR should be always above than MOR. If the HOR is below than MOR, HOR should be HOR standard (refer to Table 5).

Table 5. Equations for observing the minimum operating rate (MOR) standard.

Category	HOR > M_OR	No.	HOR < M_OR	No.
HOR modification	HOR accepted	(7)	HOR = M_OR	(8)

- Phase 3: Check for the ERR standard: also the FC system has ERR constraint. Therefore, hourly fluctuation rate of HOR should be less than ERR. If the hourly fluctuation rate of HOR excesses the ERR, the HOR should be modified refer to Table 6.

Table 6. Equations for modification the hourly operating rate in accordance with the E_RR.

Category	$HOR_{T2} > HOR_{T1} \times (1 + E_RR)$	No.	$HOR_{T2} < HOR_{T1} \times (1 - E_RR)$	No.
HOR modification	$HOR_{T2} = HOR_{T1} \times (1 + E_R R)$	(9)	$HOR_{T2} = HOR_{T1} \times (1 - E_R R)$	(10)

where, HOR_{T1} is the hourly operating rate of the FC system at some point; HOR_{T2} is the hourly operating rate of the FC system at one-hour after than $_{T1}$.

- Phase 4: Calculation of the electricity/heat efficiency on the hourly basis: the FC system energy performance (*i.e.*, electricity and heat energy efficiency of the FC system) can be differ based on the HOR as mentioned above. The New and Renewable Energy Laboratory (NREL) of U.S. developed Fuel Cell Power Model (FCP Model) which provides the electricity and heat energy efficiency information of the FC system by HOR [66].

- Phase 5: Calculation of the electricity/heat energy supply: Based on the established electricity/heat energy efficiency, the electricity/heat supply of the FC system can be calculated using energy simulation "RETScreen" or the "*proposed simplified equations*" (refer to Table 7).

Table 7. Equations for calculation of the electricity/heat supply of the FC system.

Category	Electricity	No.	Heat energy	No.
In the case of FPCO	$HFES_E = OS_I \times HOR_{FPCO}$	(11)	$HFES_H = (HFES_E / EE) \times HE \times \Omega$	(12)
In the case of PLF	$HFES_E = OS_I \times HOR_{PLF}$	(13)	$HFES_H = (HFES_E / EE) \times HE \times \Omega$	(14)
In the case of HLF	$HFES_E = (HFES_H / \Omega / HE) \times EE$	(15)	$HFES_H = OS_I \times (HE / EE) \times HOR_{HLF} \times \Omega$	(16)

where, $HFES_E$ is the hourly FC system energy supply of electricity; $HFES_H$ is the hourly FC system energy supply of heat; HOR_{FPCO} is the hourly operating rate of the FC system at full power capacity output scheme; HOR_{PLF} is the hourly operating rate of the FC system at power load following scheme; HOR_{HLF} is the hourly operating rate of the FC system at heat load following scheme; EE is the electricity efficiency of the FC system; HE is the heat efficiency of the FC system; Ω is the NRE system pipe loss coefficient (0.95).

The energy production by FC system is calculated using "energy simulation (RETScreen)" and "proposed self-production program". By evaluating achievement of the target production with constraints, the scenarios that satisfy the criteria are selected, and the LCC and $LCCO_2$ analysis are performed on these scenarios. In this study, scenarios of FC system are made by considering FC system type (4 types), operating size (12 sizes), monthly minimum operating rate (10 rates) and monthly operating scheme (3 types).

3.4. Step 4: Selecting Optimal System through Life Cycle Cost and Life Cycle CO_2 Analysis

The developed process was applied to the residential building, which considered the standard of a government subsidy. Table A2 shows the boundary conditions of the LCC and $LCCO_2$ analysis. This study selected the optimal FC system in terms of the LCC and $LCCO_2$ as follows (refer to Table 8): (i) net present value (NPV_{20}); (ii) break-even point (BEP_{20}); (iii) saving to investment ratio (SIR_{20}); and annual primary energy saving ($APES_{20}$).

- In terms of NPV_{20}, BEP_{20}, SIR_{20}, the optimal size is 100 kW (*i.e.*, scenarios #1–#3) (reached BEP_{20} in 7th and 11th year). If the energy surplus of the fuel cell system is higher than the energy demand of a given building (more than 200 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 100 kW, at which the energy supply of the fuel cell system came closest to the energy demand of a given building. Monthly minimum operating rate and operating schemes are different, because the monthly minimum operating rate and operating schemes have changed up to the building energy consumption.

- In terms of $APES_{20}$, the optimal scheme is PLF scheme and the optimal size is 300 kW (*i.e.*, scenario #4). 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. Therefore, in case of only considering $APES_{20}$, PLF is the optimal scheme.

The proposed process can be used for establishing the optimal implementation strategy of other NRE systems depending on the energy demand of a given building. In addition, the proposed process could be applied to any other country or any other type of building.

Table 8. Selecting optimal system through life cycle cost and life cycle CO_2 Analysis.

Optimal Scenario	Scenario # 1 (In terms of NPV_{20})	Scenario # 2 (In terms of BEP_{20})	Scenario # 3 (In terms of SIR_{20})	Scenario # 4 (In terms of $APES_{20}$)
$APES_{20}$: Annual Primary Energy Saving (TOE)	437.35	437.35	408.54	1071.24
NPV_{20}: Net Present Value (US $)	1,080,549	1,080,549	903,945	−1,147,030
SIR_{20}: Saving-to Investment Ratio	1.964	1.964	2.058	0.649
BEP_{20}: Break-Even-Point (Year)	7	7	11	20
Type of Fuel Cell	MCFC	MCFC	PAFC	MCFC
Operating Size	100 kW	100 kW	100 kW	300 kW
Minimum Operating Rate_Jan. (5%–50%, 5%)	10	35	25	10
Minimum Operating Rate_Feb. (5%–50%, 5%)	15	15	15	10
Minimum Operating Rate_Mar. (5%–50%, 5%)	30	40	30	30
Minimum Operating Rate_Apr. (5%–50%, 5%)	10	50	10	30
Minimum Operating Rate_May (5%–50%, 5%)	5	10	10	25
Minimum Operating Rate_Jun. (5%–50%, 5%)	25	50	40	20
Minimum Operating Rate_Jul. (5%–50%, 5%)	30	50	50	30
Minimum Operating Rate_Aug. (5%–50%, 5%)	10	40	10	10
Minimum Operating Rate_Sep. (5%–50%, 5%)	25	50	35	20
Minimum Operating Rate_Oct. (5%–50%, 5%)	25	25	25	25
Minimum Operating Rate_Nov. (5%–50%, 5%)	50	30	50	25
Minimum Operating Rate_Dec. (5%–50%, 5%)	15	15	15	15

Table 8. *Cont.*

Optimal Scenario	Scenario # 1 (In terms of NPV_{20})	Scenario # 2 (In terms of BEP_{20})	Scenario # 3 (In terms of SIR_{20})	Scenario # 4 (In terms of $APES_{20}$)
Monthly Operating Scheme_Jan. (FPCO = 1, PLF = 2, HLF = 3)	1	2	2	2
Monthly Operating Scheme_Feb. (FPCO = 1, PLF = 2, HLF = 3)	3	2	3	3
Monthly Operating Scheme_Mar. (FPCO = 1, PLF = 2, HLF = 3)	3	3	3	2
Monthly Operating Scheme_Apr. (FPCO = 1, PLF = 2, HLF = 3)	3	3	3	2
Monthly Operating Scheme_May (FPCO = 1, PLF = 2, HLF = 3)	2	1	2	2
Monthly Operating Scheme_Jun. (FPCO = 1, PLF = 2, HLF = 3)	1	1	1	2
Monthly Operating Scheme_Jul. (FPCO = 1, PLF = 2, HLF = 3)	2	3	1	2
Monthly Operating Scheme_Aug. (FPCO = 1, PLF = 2, HLF = 3)	1	1	1	2
Monthly Operating Scheme_Sep. (FPCO = 1, PLF = 2, HLF = 3)	2	1	3	2
Monthly Operating Scheme_Oct. (FPCO = 1, PLF = 2, HLF = 3)	2	3	3	2
Monthly Operating Scheme_Nov. (FPCO = 1, PLF = 2, HLF = 3)	1	3	3	2
Monthly Operating Scheme_Dec. (FPCO = 1, PLF = 2, HLF = 3)	2	2	2	2

4. Conclusions

This study aimed to develop the process for the implementation of NRE system in a building for the optimal design by considering environmental and economic effects in South Korea. Toward this end, this study was conducted in four steps: (i) establishing the basic information for the system installation; (ii) selecting key factors affecting system performances; (iii) making possible alternatives of the system installation; and (iv) selecting optimal system by considering environmental and economic effects. To validate the process for the implementation of NRE system in a building, this study conducted a case study on "J" multi-family housing complex focused on FC system, since there are easily applicable to buildings. By conducting a multilateral analysis on the results of the energy simulation, the energy generation (or substitution) effect was evaluated by applying the FC systems as NRE systems. Furthermore, LCC analysis with the analysis of the $LCCO_2$ (e.g., CO_2 emissions by energy consumption), was conducted to assess the environmental and economic effects of the implementation of the NRE system using several methods, such as the NPV, BEP and SIR methods.

In terms of NPV_{20}, BEP_{20}, SIR_{20}, the optimal size is 100 kW (reached BEP_{20} in 7th and 11th year). In terms of $APES_{20}$, the optimal scheme is PLF scheme and the optimal size is 300 kW (*i.e.*, scenario #4). In conclusion, it was shown that the FC system would be suitable at "J" multi-family housing complex in terms of environmental and economic aspect.

The results of this study could benefit potential NRE systems users and give new value in terms of system application in several ways: (i) determine which NRE system is most appropriate for a specific facility; (ii) decide which location is proper for the implementation of the NRE system by considering the characteristics of the regional climate; (iii) maximize the environmental and economic benefits of the system through the LCC and $LCCO_2$ analyses; (iv) maximize the efficiency and utilization of the system by considering key factors affecting system performances; and (v) consequently select the optimal NRE system according to the target facility and the users' preference.

Meanwhile, the following multi-dimensional analyses are suggested to be performed in the future research: (i) various analyses of other NRE system, such as the PV and GSHP systems; (ii) comparative analysis of the effects of implementing energy-saving techniques (ESTs) and NRE systems; and (iii) sensitivity analysis of the NRE systems by considering the recent trends in the reduction of the initial investment cost and in the improvement of the energy generation efficiency.

With regard to this, the research team is currently developing a multi-objective optimization system for determining the optimal solution in NRE systems simply by entering the optimization parameters (*i.e.*, several key factors) [67]. The system is developed by combining the energy simulation software program, "RETScreen and Energy plus", to design the detailed NRE systems with the concept of the optimization algorithm. It can propose the optimal key factor affecting system performance and optimal scenario of the NRE systems.

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Author Contributions

All authors read and approved the manuscript. All authors contributed to this work, discussed the results and commented on the manuscript at all stages. Chan-Joong Kim discussed the main idea behind the work and reviewed and revised the manuscript. Taehoon Hong gave precious advice on the establishment of the framework as well as in the design process. Jimin Kim led the development of the paper and conducted the LCC and $LCCO_2$ analysis. Daeho Kim developed the model with the co-authors and helped to understand the NRE systems more thoroughly. Dong-yeon Seo examined thoroughly the case study of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Appendix

Table A1. Specifics of four types of a FC 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	8571	7660	6545
Heat recovery efficiency (%)	50%	48%	43%	35%
Operating temperature (°C)	25–80	200	650	800
Initial cost ($/kW)	5712	4284	4284	7235
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 FC; [2] PAFC stands for phosphoric acid FC; [3] MCFC stands for molten carbonate FC; and [4] SOFC stands for solid oxide FC.

Table A2. Boundary conditions of LCC and $LCCO_2$.

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 and maintenance cost	Replacement/repair cost Energy consumption cost Progressive tax
	Operation and maintenance benefit	Gas savings, electricity savings Benefit from SMP Benefit from $KCER_s$

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