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Review

Advanced Strategies for Net-Zero Energy Building: Focused on the Early Phase and Usage Phase of a Building's Life Cycle

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Received: 30 October 2017; Accepted: 6 November 2017; Published: 8 December 2017

Abstract: To cope with 'Post-2020', each country set its national greenhouse gas (GHG) emissions reduction target (e.g., South Korea: 37%) below its business-as-usual level by 2030. Toward this end, it is necessary to implement the net-zero energy building (nZEB) in the building sector, which accounts for more than 25% of the national GHG emissions and has a great potential to reduce GHG emissions. In this context, this study conducted a state-of-the-art review of nZEB implementation strategies in terms of passive strategies (i.e., passive sustainable design and energy-saving technique) and active strategies (i.e., renewable energy (RE) and back-up system for RE). Additionally, this study proposed the following advanced strategies for nZEB implementation according to a building's life cycle: (i) integration and optimization of the passive and active strategies in the early phase of a building's life cycle; (ii) real-time monitoring of the energy performance during the usage phase of a building's life cycle. It is expected that this study can help researchers, practitioners, and policymakers understand the overall implementation strategies for realizing nZEB.

Keywords: net-zero energy building; passive strategies; active strategies; advanced strategies

1. Introduction

1.1. Research Background

According to key climate observation agencies such as the National Oceanic and Atmospheric Administration, the earth's average temperature in 2016 (i.e., 14.83 °C) was the highest in the history of weather observation, and the earth's average temperature also broke the record for three consecutive years, from 2014 to 2016 [1]. South Korea also recorded the highest average temperature (i.e., 13.6 °C) in the history of weather observation due to the effect of global warming [2]. These increases in global average temperature were largely attributed to the GHG effect of human activity (e.g., consumption of fossil fuels such as petroleum, natural gas, coal, etc.) and not of a natural phenomenon (e.g., El Nino) [3]. For this reason, meteorologists were worried about the serious effects of climate change on all areas of human life, such as agriculture, national security, national health, water supply, and disease, and called on countries to establish the countermeasures.

In response to these global climate change problems, 'Post-2020' was launched through the 21st Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21) held in Paris, France in December 2016 [4]. In response, South Korea set an active goal of 37% GHG reduction (i.e., 3.15 million ton·CO_2eq.) by 2030 compared to the business-as-usual level. Also, in the building sector, which accounts for approximately 25% of the national GHG emission, South Korea established the goal of reducing its GHG emissions by 35.8 million ton·CO_2eq. [5]. Toward this end, the government of South Korea continues to exert various efforts to promote sustainable development in the building sector as follows: (i) establishing a road-map for implementing nZEB (i.e., step 1: foundation for the implementation of nZEB (2014–2016), step 2: inducing the commercialization of nZEB (2017–2019), and step 3: executing obligation of nZEB (2020–)), (ii) implementing the zero-energy building certification system from 30 January 2017; and (iii) preparing a plan to promote nZEB for climate change response [6].

With this background, this study analyzed the various studies that have been conducted to address the current global climate problems, focusing on the building sector. In other words, this study aimed to systematically organize the current technologies related to nZEB through a holistic review of the existing studies that had been conducted to solve climate change problems. In addition, this study presented several future directions of reference when energy researchers or policymakers consider ways of vitalizing nZEB through technology analysis and policy introduction.

1.2. Outline

In Section 2, extensive literature review was conducted with respect to the various strategies that were used to implement nZEB for the last 10 years, according to the following two perspectives: Part A—passive strategies; and Part B—active strategies (refer to Figure 1).

(1) Part A—Passive strategies: To help realize nZEB through the reduction of the building energy demand (e.g., heating and cooling load, etc.) by introducing architectural design techniques in the early design stage [6]. Also, it can be divided into the following two categories: Part A-1: passive sustainable design; and Part A-2: energy-saving techniques (EST);
(2) Part B—Active strategies: After reducing the building energy demand through passive strategies, the residual load can be saved via the active strategies, such as RE [6]. There are two categories of active strategies for implementing nZEB: Part B-1: RE; and Part B-2: a back-up system for RE.

Section 3 proposed the advanced strategies, which take a step forward from existing strategies for implementing nZEB in terms of future directions and challenges, taking into account the building's life cycle (i.e., planning, design, construction, operation, maintenance, and disposal).

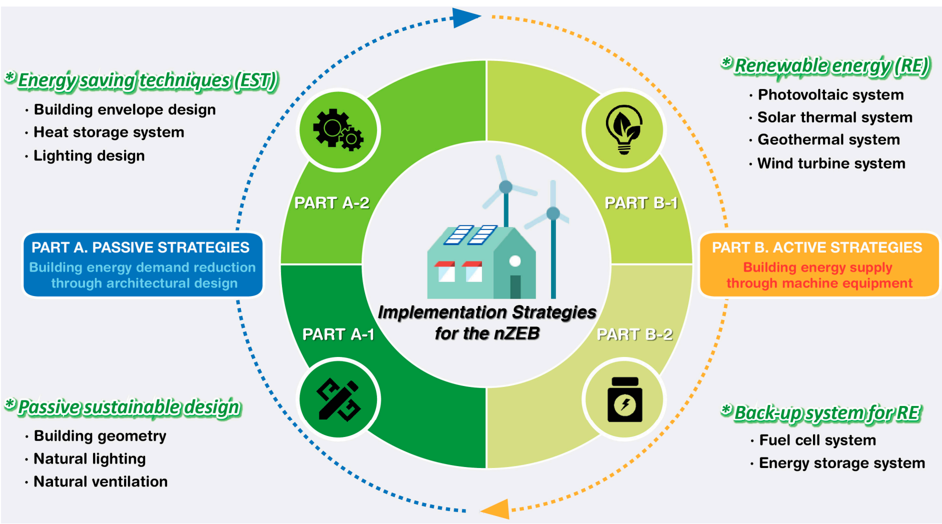

Figure 1. Passive and active strategies for implementing net-zero energy building.

2. A Holistic Review of the Implementation Strategies of nZEB

Based on the basic concept of nZEB (i.e., a building that reduces the initial load through passive strategies, and then saves the remaining residual load through active strategies, so that the sum of the amount of energy consumption and energy generation is zero), this study conducted an extensive literature review on passive and active strategies for implementing nZEB [7].

2.1. Part A: Passive Strategies

The previous studies associated with passive strategies for implementation of nZEB have mainly been divided into two categories based on the two aspects of passive sustainable design and EST. First, passive sustainable design in terms of passive strategies implies reducing the building energy demand considering the building's geographical (e.g., longitude, longitude, and altitude) and meteorological (e.g., temperature, humidity, sunshine duration, and wind speed) factors. Second, EST in terms of passive strategies refers to reducing the building energy demand by enhancing the insulation and sealing capabilities through the use of improved building materials (e.g., thermal insulation, shading, etc.).

2.1.1. Part A-1: Passive Sustainable Design

There are various methods for passive sustainable design (e.g., site planning, layout planning site plan, natural lighting, natural ventilation, etc.), which can reduce the energy consumption by considering the building's geographical and meteorological factors. In this study, the past studies on such various methods for passive sustainable design were analyzed by dividing them into three categories considering the progression of studies: (i) building geometry; (ii) natural lighting; and (iii) natural ventilation. In this study, the existing studies on these three factors are summarized in Tables 1–3.

(1) Building geometry: Building energy demand is greatly influenced by a building's composition and shape. Thus, almost all the previous studies related to building geometry evaluated building energy performance by focusing on the surrounding environment (i.e., site slope) and plan form (refer to Table 1) [8–15]. For example, De Castro and Gadi (2017) compared the annual energy savings according to the site slope within the range of 0~50° to find out the ideal design by considering the topography. As a result, it is shown that the 30° site slope and box-type design is the optimal design with the highest energy-saving potential via the 'EnergyPlus' software program [8]. Choi et al. (2012) investigated the energy consumption patterns according to four high-rise-apartment plan layouts (e.g., plate and tower type) and two living types (i.e., general-use, mixed-use) through questionnaires and a field study for evaluating the building energy performance (i.e., electricity consumption, gas consumption, and CO_2 emissions). This study showed that the electricity consumption of plate-type buildings was lower than that of tower-type buildings, but their gas consumption was higher. In addition, from the perspective of a building's living type, mixed-use buildings generated more CO_2 emissions than the general residential buildings [10]. Asadi et al. (2014) and Mottahedi et al. (2015) evaluated the energy consumption using the multilinear regression analysis and Monte Carlo simulation by considering a total of 7 building shapes (i.e., L, U, T, H, triangle, rectangle, rectangle min-corner) and 17 design variables (e.g., orientation, insulation, occupant schedule, etc.). As a result of the analysis of the annual energy consumption according to the seven building shapes, it was determined that the H shape of the building in the Texas climate zone had the highest energy consumption among all the shapes studied [11,15].

(2) Natural lighting: Through an in-depth analysis of the sun's altitude, the amount of daylight, etc., many researchers have conducted various studies on how to determine the optimal orientation of a building and on designing the atrium from the perspective of introducing the natural light system for nZEB implementation (refer to Table 2) [16–28]. First, there are various studies

related to determination of the optimal orientation of a building for reducing the building energy demand [16–20]. Abanda and Byer (2016) assessed the impact of the building orientation on building energy consumption using building information modeling according to the following three-step process: (i) building design through the Revit software program; (ii) conversion to a numerical value based on Green Building Studio, one of the leading energy simulation programs; and (iii) analysis of the effect of building orientations on the annual energy usage of a building. From the analysis results, the optimal building orientation in terms of the annual electricity and gas consumption was derived as south (i.e., building orientation of +180° from north), and the difference in energy cost savings throughout a 30 year period between the best and worst (i.e., the orientation of +45° from north) orientation was determined as £878 [17]. Hemsath (2016) aimed to analyze the impact of the building orientation on the building energy consumption and annual costs for four different geographical locations in U.S. (i.e., Lincoln, New York, Miami, and Phoenix) at the community and individual house levels. Compared to an individual house's optimal orientation, the mean of planning that considers the optimal building orientation at a community level was analyzed to more effectively reduce the annual energy cost [19]. Second, various studies have been carried out for efficient atrium design because the atrium shape is a very important factor in natural lighting [21–28]. Nasrollashi et al. (2015) assessed the impact of the atrium-to-total building area ratio in terms of the energy efficiency and indoor environmental conditions, using the DesignBuilder software program. As a result of this study, setting the atrium-to-total building area ratio as 1/4 was determined to be the most effective in terms of energy performance, daylighting, and thermal comfort (i.e., predicted mean vote) [25]. Mohsenin and Hu (2015) evaluated the daylight of an office building according to the atrium type (i.e., central, attached, and semi-enclosed), atrium proportions (i.e., Well Index), and roof aperture designs (i.e., monitor roof and horizontal skylight) through the DIVA software program as the climate-based daylighting modeling tool [26].

(3) Natural ventilation: To implement nZEB, an architectural design for inducing the reduction of the building energy demand through the effective influx of the outdoor air (i.e., natural ventilation) should be considered in the initial design stage. Generally, natural ventilation can be categorized based on two mechanisms: (i) buoyancy-driven ventilation by the vertical and horizontal temperature difference; and (ii) wind-driven ventilation by the pressure difference between the front and the back of the building (refer to Table 3) [29–38]. First, there are various previous studies related to buoyancy-driven ventilation [29–34]. Li and Liu (2014) focused on the thermal performance of phase-change-material (PCM)-based solar chimney within laboratory conditions with three different heat fluxes (500, 600, and 700 W/m^2). Through this study, it was confirmed that PCM-based solar chimney can achieve the time-shifting of solar energy, which can induce more effective natural ventilation compared to the general solar chimney, based on the large thermal energy storage capacity of PCM [31]. Acred and Gary (2014) proposed a design strategy of stack effect ventilation for a multi-story atrium building based on a simplified mathematical model. The dimensionless charts that can determine the combination of design variables were developed as a guideline for realizing natural a ventilated building [30]. Second, there are various previous studies related to wind-driven ventilation [35–38]. Nejat et al. (2016) conducted a comparative analysis of the wind-catcher-integrated wing wall (i.e., new design) and the conventional wind catcher via the Computational Fluid Dynamics (CFD) software program and wind tunnel testing. As a result, the ventilation performance of the wind-catcher with a 30° wing wall angle was superior to the other designs (45° and 60°). Also, the ventilation performance of the new design was improved by 50% compared to the conventional wind catcher [37]. Mei et al. (2017) analyzed the ventilation performance according to the building density level in an urban residential neighborhood using the CFD software program. In addition, this study presented a strategy for establishing the optimal neighborhood building layout design in terms of ventilation performance (i.e., pollutant level) [38].

(4) Discussion: In this study, research related to passive sustainable design was analyzed, focusing on building geometry, natural lighting, and natural ventilation. First, from the viewpoint of building geometry, previous studies have focused on energy savings according to the building shape and building density. Second, from the viewpoint of natural lighting, most previous studies centered on reducing the lighting, cooling, and heating load depending on the shape and size of the atrium and the building's orientation. Finally, from the view point of natural ventilation, previous studies analyzed the energy-saving potential and ventilation performance focused on buoyancy-driven ventilation and wind-driven ventilation. In other words, if a building is designed with factors of building geometry, natural lighting, and natural ventilation being taken into consideration at the beginning of the process, the following effects can be obtained: 20% energy efficiency improvement, 25% heating, and 10–30% cooling load reduction [12,21,33]. However, it is still insufficient to consider only passive sustainable design in terms of implementing nZEB. Therefore, future studies from the perspective of nZEB need to be applied not only with passive sustainable design, but also with energy-saving techniques (EST) and active strategies.

Table 1. Literature review on the building geometry in terms of passive sustainable design.

Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
Tuhus-Dubrow et al. (2010) [9]	Total seven building shape (e.g., rectangle and cross shape)	Optimal building shape, life cycle cost/utility cost	Genetic algorithm	USA	• The results indicate that the rectangular and trapezoidal type of building have lowest life-cycle-cost throughout U.S. five different climates
Choi et al. (2012) [10]	Building type (i.e., mixed-use and general apartment), shape (i.e., tower and plate type)	Electricity/gas consumption	Survey and research	Korea	• Tower type and mix-used apartment consumed more energy and emitted more CO_2 than plate type
Parasonis et al. (2012) [12]	Building density, relative geometry efficiency (i.e., ratio of surface area to building volume)	Annual energy savings	Mathematical model	Lithuania	• Changes of the building density can improve the energy efficiency by up to 20%
Parasonis et al. (2012) [13]	Building density, relative geometry efficiency (i.e., ratio of surface area to building volume)	Annual energy savings	Mathematical model	Lithuania	• The geometric efficiency of a building depends both on its size and proportions
Asadi et al. (2014) [11]	Total seven building shapes (e.g., triangle and rectangle shapes)	Annual energy consumption	Multi-linear regression analysis	USA	• The H-type buildings in the Texas climate zone had the highest energy consumption compared to the other shape type buildings
Hemsath and Bandhosseini (2015) [14]	Ratio of plan's length to width, stacking level	Annual energy consumption	Global sensitivity analysis	USA	• Building's geometric properties depending on location have a bigger impact on buildings energy performance than the material (e.g., U-value, solar heat gain coefficient, etc.)
Mottahedi et al. (2015) [15]	Total seven building shapes (i.e., triangle, rectangle, mincomer, L, U, T, and H Shapes)	Annual energy consumption	Multi-linear regression analysis	USA	• T-shape buildings showed the highest total energy used in almost U.S. climate zones
De Castro and Gadi (2017) [8]	Total five slope-adaptive building designs (e.g., single-level and spilt-level), site slope level within the range of 0~50°	Monthly average load, annual energy saving	EnergyPlus	Portugal	• The 30 degrees of site slope level and box type design is the ideal adaptive design

Table 2. Literature review on the natural lighting in terms of passive sustainable design.

Classification	Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
Orientation	Fallahtafti and Mahdavinejad (2015) [16]	Orientation, building geometry, window-to-wall ratio (WWR)	Heating gain/loss	Mathematical model	Iran	• The optimal orientation of a building rely on its compactness, additionally WWR has the most correlation in decision for orientation
	Abanda and Byer (2016) [17]	U.K electricity price, gas price, orientation (interval: 45°)	Annual CO_2 emissions	Revit, BIM, Green Building Studio	UK	• Appropriate orientated building can save up to £878 worth of energy over a lifetime
	de Vasconcelos et al. (2016) [18]	Orientation, discount rate	Global energy cost, energy consumption	Life cycle cost analysis	Portugal	• Considering both building orientation and Portuguese discount rate can help making a decision on a cost-optimal solution for energy efficiency
	Hemsath (2016) [19]	Orientation, climate factors	Annual energy costs, optimal orientation	BEopt, EnergyPlus	USA	• Community orientation has more impact on the energy savings in comparison to individual household's orientation
	Valladares-Rendon et al. (2017) [20]	Climate factors	Worldwide guide of azimuth angle	Case study, Ecotect	Hong Kong (China)	• Guided angle for 59 locations, 58.62% are optimized to south orientation, 18.98% to the southeast, 12.06% to the north, 5.17% to the northwest, and 5.17% to the northeast
	Assadi et al. (2011) [21]	Glass height and diameter	Thermal efficiency	Mathematical model	Iran	• Designing atrium decreases the heating load up to 25% for an institutional building at the maximum glass height
	Aldawoud (2013) [22]	Atrium dimensions, atrium geometry ratio	Annual energy consumption	DOE2.1	Saudi Arabia	• The square shaped atrium is superior to other designs (e.g., the narrow, elongated atrium) in terms of energy consumption
	Chow et al. (2013) [23]	-	Energy savings of each floors	Field study	Hong Kong (China)	• Annual energy savings is 43,003 kWh and the annual average CO_2, SO_2, NO_x might be decreased by 3,225,244,042.4 kg

Table 2. *Cont.*

Classification	Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
Atrium	Taleghani et al. (2014) [24]	Wind speed	Energy demand	EnergyPlus	The Netherlands	• From May to August, the energy efficiency of atrium is maximized during the whole year
	Nasrollashi et al. (2015) [25]	Atrium ratio, internal heat load	Annual energy consumption, comfort indices	Mathematical model	Iran	• Lessening the atrium ratio reduces the annual amount of energy consumption and daylight amounts
	Mohsenin and Hu (2015) [26]	Well index (i.e., atrium proportion), atrium types (e.g., semi-enclosed), aperture types (e.g., horizontal skylight)	Useful daylight illuminance	DIVA	USA	• Atrium Well Index is an important indicator to decide atrium proportion and to comparing daylight illuminance in atrium.
	Danielski et al. (2016) [27]	Building design (e.g., atrium), envelope parameter (e.g., U-value)	Energy demand	Questionnaire, VIP-Energy software	Sweden	• The application of heated atrium to Nordic climate can reduce total final energy demand. • Results of questionnaire indicate that atrium in complex households facilitates social interaction.

Table 3. Literature review on the natural ventilation in terms of passive sustainable design.

Classification	Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
	Hussain and Patrick (2012) [29]	Solar intensity, floor property (e.g., depth, width, and height)	Volume flow rate, thermal comfort	CFD simulation	-	• Buoyancy-driven natural ventilation is facilitated from atrium space integrated with solar chimney on the roof
	Acred and Gary (2014) [30]	Heat transfer parameter	Air flow rate	Mathematical method	UK	• Air flow control must be shared between all openings in the building to minimize the inter-floor flow rate imbalance

Table 3. *Cont.*

Classification	Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
Buoyancy-driven ventilation	Li and Liu (2014) [31]	Solar intensity (i.e., 500–700 W/m^2), phase change material (PCM) thermos-physical properties	Air flow rate	Mathematical method	UK	• It was confirmed that PCM-based solar chimney can achieve the time-shifting of solar energy, which can induce more effective natural ventilation compared to the general solar chimney, based on the capacity of PCM
	Jing et al. (2015) [32]	Solar intensity (i.e., heat flux), gap to height ratio (i.e., 0.2~0.6)	Air flow rate	Experiment	China	• Optimal gap-to-height ratio (i.e., the area of the aperture to the height of the chimney) for promoting natural ventilation in solar chimney is about 0.5
	He et al. (2017) [33]	Architectural design (e.g., orientation, building envelope), climate	Energy savings, thermal comfort	Mathematical method	China	• Natural ventilation is an effective way to improve thermal comfort while maintaining low cooling demand in hot–humid summer zones • Using natural ventilation can reduce cooling demand by 10–30% compared to not using natural ventilation
	Tong et al. (2017) [34]	Weather (e.g., temperature, wind), season	Natural ventilation potential	Atmospheric boundary layer, meteorology model	USA	• Among studied cities (i.e., New York, Los Angeles, Chicago, and Minneapolis), Los Angeles provides the most ideal climate for utilizing natural ventilation (i.e., 7258 natural ventilation hours or 83% of the year at ground level)

Table 3. *Cont.*

Classification	Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
Wind-driven ventilation	Afshin et al. (2016) [35]	Wind angle, inlet wind speed	Air flow rate	Mock up experiment	Iran	• The two-sided wind-catcher with the highest ventilation rate occurs at the angle of 90°
	Nejat et al. (2016) [36]	Wind speed, wind-catcher angle (i.e., 30, 60, 90°)	Air flow rate, CO_2 concentration	Experiment, CFD simulation	Malaysia	• Propose a new solution to short-circuiting, which is a common problem for conventional wind-catcher
	Nejat et al. (2016) [37]	Wind speed, wing wall angle (i.e., 30, 45, 60°)	Air change hour, air flow rate	Mock up experiment	Malaysia	• The wind-catcher with wing wall angle of 30° shows optimal ventilation performance among other designs • The new design (i.e., wind-catcher with wing wall) is much better in ventilation performance than conventional wind-catcher
	Mei et al. (2017) [38]	Building densities (i.e., medium (0.25) and compact (0.44) urban development)	Wind flow	CFD simulation	China	• When low level of building density is maintained, the ventilation rate increases • Depending on the neighborhood composition characteristics (e.g., building block array), the breathability of city is greatly affected

2.1.2. Part A-2: Energy-Saving Techniques (EST)

This study examined the existing studies related to EST in terms of passive strategies in the following three categories: (i) building envelope design; (ii) heat storage system; and (iii) lighting design. In addition, Tables 4–6 summarized the previous studies related to EST systematically.

(1) Building envelope design: As the building envelope is directly against the external environment, it plays an important role in energy consumption (e.g., heating and cooling demand) [39]. Accordingly, a variety of studies have been carried out in relation to the reduction of the building energy demand through the envelope design. In this study, the above-mentioned past studies can be classified into heat insulation, opening design, and shading device (refer to Table 4) [40–55]. First, in terms of the heat insulation, the studies that have been carried out to reduce buidling energy demand are as follows [40–45]. Pomponi et al. (2015) evaluated CO_2 emissions and energy consumptions in terms of building life cycle by comparing various façade strategies (i.e., double-skin facade, traditional up-to-standard, and single skin). As a result of the analysis, it was confirmed that applying the double-skin façade of building has the best carbon-saving potential [44]. Tam et al. (2016) assessed the technical performance and cost-effectiveness of the green roof as a heat insulation in Hong Kong through a questionnaire survey, interviews, and field studies. Also, the results showed that the room temperature can be lowered by 3.4 °C when the green roof is applied [45]. Second, in terms of the window design, most of the previous studies mainly focused on the derivation of an optimal design solution considering that the window is more vulnerable to heat gain and loss than the wall is [46–51]. Goia (2016) examined the optimal window-to-wall ratio (WWR) for four cities (i.e., Oslo, Frankfurt, Rome, and Athens) located in the mid-latitude region of Euroupe through the EnergyPlus software program. These cities all showed an optimal energy performance within the range of 30–45% of the WWR [49]. Wen et al. (2017) aimed to develop a guideline that would enable the designer to determine the suitability of the WWR in the early design stage. As a result, the distribution of the optimal WWR in Japan was mapped out by considering the window properties (e.g., U-value, visible transmittance, etc.) and meteorological factors (i.e., mean external temperature and mean global solar radiation) [50]. Finally, in terms of the shading device, several studies have been conducted to foind a way of lowering the building energy demand [52–55]. Kim et al. (2012) investigated the various type of external shading devices (e.g., overhang, blind, etc.) in terms of energy savings for heating and cooling, via the IES_VE software program. Through this study, it was concluded that the external shading device had a better technical performance than the internal shading device [52].

(2) Heat storage system: Various studies associated with the heat storage system have been conducted because the heat capacity of a building is a very important factor from the point of view of nZEB. This study examined the previous studies that analyzed the energy reduction according to the building thermal performance, focusing on the thermal mass and trombe wall (refer to Table 5) [56–66]. First, there are many previous studies that focused on reducing the heating and cooling demand of a building through the heat storage function of the thermal mass [56–61]. Ma and Wang (2012) conducted a numerical analysis of the dynamic heat transfer performance of the interior planer thermal mass according to the thermal mass thickness (i.e., 0.025~0.70 m) and type (i.e., wood, concrete, and steel). It was found that the heat storage ability of the thermal mass relies on the thermal mass thickness for reaching a superlative value [58]. Chernounsov and Chan (2016) analyzed the thermal performance of the building-envelope-integrated PCM with a high specific heat capacity using the EnergyPlus software program for an office building in Hong Kong. Through this study, the relationship between the indoor thermal environment and the PCM's thickness, placement, and orientation was analyzed [61] Second, the past studies related to the trombe wall, which functions as a heat storage system by applying a solar heating collector made of double glazing on the wall, are as follows [62–66]. Bojic et al. (2014) conducted a comparative analysis of the environmental performance (i.e., primary energy for heating during winter and

annual energy consumption) according to the application of the trombe wall. As a result of the analysis, it was shown that 20% annual energy-saving is possible when the trombe wall is applied [64] Bajc et al. (2015) focused on the impact analysis of the building energy demand of a passive house with the trombe wall via CFD simulation considering the Belgrade weather. The results showed that the trombe wall increased the cooling demand in summer, but it is very suitable for the Belgrade climate because of its efficient heating energy-saving in winter [66].

(3) Lighting design: From the perspective of nZEB implementation, this study analyzed the previous studies focused on the lighting emitting diode (LED), light shelves, and lighting control system as methods for reducing the lighting load (refer to Table 6) [67–74]. Principi and Fioretti (2014) conducted a comparative analysis of the compact fluorescent and LED in terms of their environmental performance, based on the experimental test results. Moreover, it is possible to save up to 41~50% global warming potential and cumulative energy demand by using LED rather than the compact fluorescent [68]. Meresi (2016) investigated the efficiency of daylight for the allocation of light shelves and movable semi-transparent external blind considering various design conditions, via the Radiance software program. As a result, the combination of a light shelf and semi-transparent movable external blinds can increase the daylight exploitation and can construct a uniform illuminance distribution in a room by increasing the light level at the back of the space and reducing the daylight near the window [72]. Byun et al. (2014) developed an intelligent LED control system considering the energy consumption and user satisfaction, based on multi-sensors and wireless communication technology. The proposed LED control system showed 21.9% energy savings by automatically adjusting the illuminance considering the energy efficiency [67].

(4) Discussion: In this study, existing studies related to EST are analyzed focusing on the building envelope design, heat storage system, and lighting design. In particular, due to the characteristics of the building envelope directly facing the external environment, lots of studies related to building envelope design and energy demand have been carried out, taking into consideration heat insulation, window design, and shading device. Also, for the heat storage system, various studies are under way to increase the heat storage performance of a building by applying advanced materials such as PCM. Finally, leading on from studies regarding the introduction of LEDs, studies in terms of lighting design focusing on a reduction of the lighting load through the introduction of a control system considering daylight and shading devices are being carried out. As previously mentioned, various studies are underway to reduce building energy demands, but it is not enough to focus on only EST for practical nZEB implementation. In other words, to realize nZEB, active strategies must be considered together with EST as passive strategies.

Table 4. Literature review on the building envelop design in terms of energy-saving techniques.

Classification	Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
Heat insulation	Daouas (2011) [40]	Orientation, insulation property	Annual energy load, optimum insulation thickness	Mathematical model	Tunisia	• When the optimal insulation thickness (i.e., 10.1 cm) was applied to the building, the energy saving was 71.33% and the payback period was 3.29 years
	Ottele et al. (2011) [41]	Green wall type (e.g., bare, direct, indirect)	Energy savings	Life cycle environmental analysis	The Netherlands	• Living wall system based on felt layers has the highest environmental impact
	Sanjuan et al. (2011) [42]	Open-joint ventilated façade, conventional façade	Heat flux, solar radiation	CFD simulation	Spain	• Open-joint ventilated facade has lower heat gain than conventional facade up to 26% during daylight hours
	Hong et al. (2013) [43]	Double skin façade type (i.e., box, corridor, multistory, shaft)	Saving-to-investment ratio, break-even point	Life cycle cost analysis	Korea	• Multi-story double skin facade are much more efficient than any other double skin facade in terms of the economic feasibility
	Pomponi et al. (2015) [44]	Façade type (i.e., double skin/mono), glass type (i.e., clear/coated)	Heating load, payback period	Life cycle energy and environmental analysis	UK	• Double skin facade is more energy efficient and more carbon efficient in 98% and 85% of the cases
	Tam et al. (2016) [45]	-	Measured temperature, maintenance cost	Survey and research	Hong Kong (China)	• The green-roof can lower the room temperature to 3.4 °C • Solar depth and vegetation species can impact on thermal performance

Table 4. *Cont.*

Classification	Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
Opening design	Su and Zhang (2010) [46]	WWR, orientation, glass type (e.g., single, hollow)	Environmental impact	Life cycle environmental analysis	China	• The WWR is the most influential factor in life cycle environmental impact
	MA et al. (2015) [47]	WWR (i.e., 10~100% with interval 10%), U-value	Recommended WWR	Mathematical model	USA	• The optimal WWR is determined not only by the temperature amplitude but also the U-value of the building envelope
	Seo et al. (2015) [48]	WWR, orientation, glazing type, shading type	Heating/cooling demand	DesignBuilder v3.0, Microsoft-Excel-based VBA	Korea	• This study developed the nine-node-based Lagrangian finite element model for estimating the heating and cooling load according to the WWR and orientation
	Goia (2016) [49]	WWR, orientation, building geometry, façade material	Total energy consumption, Daylight autonomy	EnergyPlus	E.U.	• The optimal WWRs of European countries in the mid-latitude were estimated to be within the range of 30~45%
	Wen et al. (2017) [50]	WWR (i.e., 10~70%, interval: 10%), orientation	Total CO_2 emission, recommended WWR	EnergyPlus	Japan	• This study presented the optimal WWR of all regions of Japan by considering the meteorological factors and window properties
	Zenginis and Kontoleon (2017) [51]	WWR, building aspect ratio (i.e., length and width dimensions)	Heat gain and loss	Mathematical model	Greek	• The façade orientation and building aspect ratio with WWR are huge impact on heat fluxes through the building

Table 4. *Cont.*

Classification	Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
Shading device	Kim et al. (2012) [52]	Shading device type (i.e., overhang, blind, light-shelf), device slat angle	Energy saving, annual heating load	EnergyPlus	Korea	• As the internal device absorbs solar heat and release to the inner space, external shading is more superior to internal devices.
	Cheng et al. (2013) [53]	Width/height of opening, ratio of length of shade device to window vertical length	Shading ratio	Mathematical model	Taiwan	• By choosing the optimal design (i.e., using proper material), shading device systems can achieve better utilization and peak efficiency than ever before
	Lin et al. (2016) [54]	Sunshade style and size (i.e., horizontal, vertical, grid), envelope material	Optimal sunshade	TRNSYS	Taiwan	• Office building envelope design model provide optimum sun shade type, sunshade length for engineer's decision
	Ye et al. (2016) [55]	Shading type (i.e., internal, external, and non-shading)	Indoor temperature, solar radiation intensity, cooling load	EnergyPlus	China	• By using proper material, internal shading can be better than external shading devices in terms of cost and maintenance

Table 5. Literature review on the heat storage system in terms of energy-saving techniques.

Classification	Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
	Diaconu (2011) [56]	PCM melting point, ventilation frequency, occupancy pattern	Indoor temperature, energy savings	TRNSYS	Romania	• The occupancy pattern influences the PCM melting point for reaching maximum energy storage capacity
	Weinlaeder (2011) [57]	Conventional/PCM integrated interior blind	Indoor/outdoor temperature	Experiment	Germany	• PCM-blind has an enormous advantage in decreasing cooling loads and providing thermal comfort

Table 5. *Cont.*

Classification	Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
Thermal mass	Ma and Wang (2012) [58]	Thermal mass thickness	Indoor temperature, maximum heat storage	Mathematical method	USA	• The heat storage ability of thermal mass relies on optimal thickness to reach maximum value
	Silva et al. (2015) [59]	Daily average solar radiation, wind direction, and intensity	Indoor/outdoor temperature	Experiment	-	• PCM-shutter benefits for thermal inertia of building thermal environment
	Turner et al. (2015) [60]	Pre-cooling period	Energy consumption, peak load reduction	REGCAP	USA	• Optimum pre-cooling strategy removes 80% of the peak load and minimize additional energy consumptions
	Chernousov and Chan (2016) [61]	Thermal mass property, internal load fraction	Indoor temperature, AC power demand	EnergyPlus	Hong Kong (China)	• PCM layers need to be less isolated on the interior to promote rapid thermal exchange
Trombe wall	Stazi et al. (2012) [62]	Wall material (e.g., concrete), glazing type, wall thickness, frame material	CO_2 emissions	EnergyPlus, Life cycle environmental analysis	Italy	• The trombe walls have an immense environmental burden both in the production and operational stages
	Abbassi et al. (2014) [63]	Trombe wall area (i.e., 0~19 m^2, interval: 1 m^2)	Heating energy savings	TRNSYS	Tunisia	• The area of trombe wall has influence the thermal efficiency; 4 m^2 areas can save up 50% of heating load and the 8 m^2 can save up to 77%
	Bojic et al. (2014) [64]	Real residential house description (e.g., wall material)	Primary energy use, energy saving	EnergyPlus	France	• When installing the trombe wall, annual energy savings are over 20% in heating season
	Briga-Sa et al. (2014) [65]	Massive wall thickness (i.e., 15~40 cm, interval: 5 cm)	Heating load	Mathematical method	Portugal	• Massive wall thickness significantly increases in the thermal performance of the trombe wall
	Bajc et al. (2015) [66]	Boundary condition (e.g., material density)	Indoor temperature, heat flux	CFD simulation	Servia	• According to CFD simulation, the trombe wall is a good alternative for good passive strategy in Belgrade weather

Table 6. Literature review on lighting design in terms of energy-saving techniques.

Authors	Design Variables	Analysis Target	Simulation Tool or Method	Country	Main Finding
Byun et al. (2014) [67]	Occupancy time, occupant movement detection	Lighting intensity	Experiment	Korea	• The intelligent household LED lighting system can cut down total energy consumption by 21.9%
Principi and Fioretti (2014) [68]	Life cycle inventory (e.g., land use, cumulative energy demand, etc.)	Environment impact	Life cycle environmental analysis	Italy	• The LED allows the environmental impacts to be reduced due to high energy saving efficiency
Xue et al. (2014) [69]	Distance from window	Illuminance, uniformity ratio (i.e., minimal illuminance/average illuminance)	Radiance, TracePro7.0	Hong Kong (China)	• Clerestory window with certain curvature angle range (44.3~90°) improves the illuminance and uniformity distribution of an inner space
Berardi and Anaraki (2015) [70]	Location of illuminance measurement, WWR	Useful daylight illuminance	Radiance	Canada	• The light shelves increase the useful daylight illuminance level up to six meters in front of the windows and provide uniform distribution
Nagy et al. (2015) [71]	Occupancy time, control mode (i.e., baseline, comfort, and savings)	Daily energy consumption	Experiment	Switzerland	• The result of six-week case study for 10 offices indicates that energy savings 37.9% were achieved compared to a standard light setting control
Meresi (2016) [72]	Location of illuminance	Daylight level/factor	Radiance	Greek	• The light shelves take advantage of daylight exploitation in classrooms and provide uniform distribution of daylight
Caicedo et al. (2017) [73]	Daylight factor, occupancy time, ceiling sensor position	Dimming level	Experiment	The Netherlands	• The smart-lighting system control system with ceiling sensors provides compatibility of energy savings and the proper illumination level in the room
Lee et al. (2017) [74]	Vent ratio (4, 6, 8, and 10 mm of diameter), angle of light-shelf	Indoor illumination, energy consumption	Experiment	Korea	• Perforated light-shelves are an alternative of conventional light-shelves that are easily damaged from outdoor wind • Energy saving efficiency is improved by widening of the reflector of perforated light-shelves

2.2. Part B: Active Strategies

There are restrictions in realizing nZEB only by applying the passive strategies proposed in Section 2.1. Therefore, to achieve nZEB, the energy consumption that was not reduced 100% through the passive strategies is to be substituted by the energy generated through the active strategies [7]. In this study, the previous studies related to the active strategies were classified into those on RE and the back-up system for RE. RE, whose use is an active strategy, refers to energy obtained from renewable resources such as sunlight, geothermal energy sources, and wind. The back-up system, on the other hand, as an active strategy, is a necessary system for the effective application of RE as a method of compensating for the instability of RE due to the external environment (i.e., weather).

2.2.1. Part B-1: Renewable Energy (RE)

This study analyzed previous studies focused on the four types of RE, whose use is an active strategy for realizing nZEB, by considering its applicability to buildings: (i) photovoltaic (PV) system; (ii) solar thermal system; (iii) geothermal system; and (iv) wind turbine system (refer to Tables 7–10).

(1) PV system: The previous studies related to the PV system mainly performed technical-economic-policy analysis in terms of two perspectives (i.e., rooftop PV system and building-integrated PV system (BIPV)) (refer to Table 7) [75–95]. First, there have been various studies on the rooftop PV system [75–82]. Ordóñez et al. (2010) investigated the energy capacity of the PV system in Andalusia, Spain considering the residential building characterization (e.g., detached house, townhouse, etc.), useful rooftop area, and PV panel installation design (i.e., distance between solar panels) using the Autodesk AutoCAD software program. According to this study, the amount of electricity generated from PV systems on a residential building's rooftop (i.e., 265.52 km^2 of the total roof surface area) is 9.73 GW/year, which is 78.89% of the total energy requirements [75]. Elibol et al. (2017) was carried out outdoor testing of the technical performance of PV panels for one year on the roof of Düzce university scientific and technology researches application and research center in Düzce Province, Turkey according to the PV panel's type (i.e., mono-crystalline, polycrystalline, and amorphous silicon (a-Si)). As a result, the efficiencies of the PV panel were 4.79, 11.36, and 13.26% for the a-Si, polycrystalline, and monocrystalline PV panel, respectively. In addition, the external temperature correlated positively with the a-Si and polycrystalline PV panel, and negatively correlated with the monocrystalline PV panel [81]. Hong et al. (2017) developed a method for predicting the amount of electricity generated from the rooftop PV system through hill shade analysis, by assessing the potential of three perspectives (i.e., physical, geographic, and technical potential). As a result of applying the developed methodology to the Gangnam district in Seoul, South Korea, the physical, geographic (i.e., the available rooftop area), and technical potentials of Gangnam district were 9,178,982 MWh, 4,964,118 m^2, and 1,130,371 MWh [82]. Second, there have been various studies on the BIPV [83–95]. Olivieri et al. (2014) evaluated the technical performance of the window-integrated semi-transparent PV system and general glazing via a package of specific software program (i.e., DesignBuilder, EnergyPlus, PVsyst, and COMFEM). It was confirmed that the window-integrated semi-transparent PV system showed 18–59% energy savings according to the façade opening compared with the reference glass [90]. Oh et al. (2017) developed a nine-node-based finite element model for estimating the techno-economic performance of building-integrated PV blind system (BIPB) through Microsoft-Excel based VBA. In addition, the economic analysis of BIPB was conducted focusing on the residential progressive electricity tariffs [95].

(2) Solar thermal system: There have been various studies that utilize solar heat by absorbing, storing, and converting it for the heating and cooling of a building based on infinite solar energy (refer to Table 8) [96–107]. Anderson et al. (2010) analyzed the effect of the color (ranging from white to black) of the solar collector both theoretically and experimentally on the thermal

performance of the building-integrated solar thermal system [96]. Mammoli et al. (2010) analyzed the techno-economic-environmental performance of a solar-thermal-assisted HVAC system by considering the season, operation time, temperature (e.g., tank temperature, solar array inlet/out let temperature, etc.), and solar heat data (e.g., solar flux, solar collector's efficiency, etc.) through experiment evaluation [97]. Bornatico et al. (2012) developed a model that could represent the optimal capacity of the solar thermal system through the particle swarm optimization algorithm and genetic algorithm by considering the meteorological data, collector area, tank volume, and size of the auxiliary power unit [99]. Chialastri and Isaacson (2017) conducted tests for a prototype of a building-integrated PV/thermal air collector which can generate thermal and electrical energy based on experiments and two-dimensional models in COMSOL Multiphysics. As a result, the maximum temperature of the prototype was 31 °C, and the average thermal and electrical efficiencies were 31% and 7%, respectively [107].

(3) Geothermal system: Many studies have been conducted on the geothermal system that can reduce the heating and cooling demand of a building based on a constant annual underground temperature of 15 °C (refer to Table 9) [108–119]. Kim et al. (2012) conducted an evaluation of the performance of the geothermal system installed in Pusan national university in South Korea based on the measured data (e.g., outdoor and indoor temperature, inlet and outlet temperature of circulating water, etc.). Towards this end, this study installed thermocouples under the ground for analyzing the characteristics of the geothermal heat exchanger's thermal diffusion, and estimated the technical performance of the geothermal system according to the heating and cooling period [34]. Sivasakthivel et al. (2012) assessed the potential reduction in CO_2 emissions and the potential for electricity-saving by introducing the geothermal system during winter in the northern region of India, considering the regional factors and the coefficient of performance of the geothermal system. This study indicated that applying the geothermal system can reduce the CO_2 emissions and electricity consumption by 0.539 and 708 GW, respectively [111]. Kim et al. (2015) conducted a comprehensive analysis of the economic and environmental performance of the geothermal system according to the entering water temperature from life cycle perspective, using the GLHEPro software program [115].

(4) Wind turbine system: As the wind speed is a very important factor for the wind turbine system, most of the previous studies on it analyzed its technical performance by applying it to the rooftop or to a high-rise building (refer to Table 10) [120–128]. Li et al. (2013) assessed the feasibility of implementing the wind turbine system in a tall building through wind tunnel tests. As a result, the building orientation, the bell-mounted shapes of the four tunnels with contracted inner sections, and the surrounding buildings were found to be important factors influencing the wind speed amplification and wind loads [124]. Lu and Sun (2014) analyzed the technical potential of wind power in urban high-rise buildings considering the wind data and building properties. Toward this end, a numerical analysis of the simulation results was conducted using the CFD and ANSYS FLUENT software program [125]. Cao et al. (2017) evaluated the wind power resource around the 1000-meter scale of mega-tall buildings in China based on the mesoscale meteorological model Weather Research and WRF v3.4 software program. According to the results of this study, the technical performance of the wind turbine system was seen to be the best when at distances of 300 and 200 m from the ground, and when the building orientation is north and south, in terms of the wind power density and the amount of electricity generated [128].

(5) Discussion: The four RE (i.e., PV system, solar thermal system, geothermal system, and wind turbine system)-related researches in this study showed the following trends. First, studies related to the PV system were mainly focused on the techno-economic performance analysis according to the PV panel type (e.g., a-Si panel, polycrystalline panel, monocrystalline panel, and semi-transparent PV system) and the development of the prediction model of the amount of electricity generated according to the design variables of the PV system. Second, related studies of the solar thermal system focused primarily on the thermal performance of a building

according to the characteristics of the solar collector (e.g., color, capacity, temperature, etc.). Third, for the geothermal system, the majority of studies carried out on energy savings and economic effects depend on design conditions (e.g., a given geothermal system's coefficient of performance, location, borehole length, etc.). Lastly, for the wind turbine system applied to building, studies were conducted mainly on high-rise building in order to analyze the amount of electricity generated and optimal design conditions by considering climate (e.g., wind date), building layout, and so on. Various efforts such as the application of high efficiency PV panels and analysis on optimal design conditions of the RE system have been carried out to improve energy self-sufficiency rate of a building through RE-related studies, but it would be very difficult to implement nZEB with only RE.

Table 7. Literature review on the PV system in terms of renewable energy.

Classification	Research	Analysis Target			Design Variables	Simulation Tool or Method	Country	Main Findings
		Technical [a]	Economic [b]	Policy [c]				
Rooftop PV system (Horizontal)	Ordóñez et al. (2010) [75]	○	-	-	Building properties, shading effect, PV installation type, solar irradiation loss from shading	AutoCAD, Google Earth	Spain	• The rooftop PV system for residential building in Andalusia will satisfy 78.89% of all energy needs
	Hong et al. (2014) [76]	○	-	-	Geographical/meteorological information	RETScreen, ArcMap 10.1, Mathematical method	Korea	• The GIS based optimization model was developed by analyzing the differences in the amount of electricity generated according to the regional factors, azimuth, and tilt of the panel
	Koo et al. (2014) [77]	○	○	○	Building information, PV panel's properties, region	Mathematical method, RETScreen	Korea	• In seven metropolitan and satellite cities, the potential of nZEB was less than 100% and the remaining eight provinces were over 100%
	Jeong et al. (2015) [78]	○	○	-	Military building's information, PV panel/inverter type	Mathematical method, RETScreen, PBECAS	Korea	• The best implementation scenario is P1-S/N in terms of absolute investment value, as it resulted in the NPV_{25} of US$1,422,454. • In terms of relative investment value, P1-S and P3-e are the best scenarios as the resulted in the SIR_{25} of 1.59 and the BEP of 16
	Park et al. (2016) [79]	○	-	○	Building/PV system/region information	RETScreen, Mathematical method	Korea	• Mono-Si PV system is more suitable for Korean educational facilities than Poly-Si PV system • The budget of application of a PV system should be determined considering the school and region type

Table 7. *Cont.*

Classification	Research	Analysis Target			Design Variables	Simulation Tool or Method	Country	Main Findings
		Technical [a]	Economic [b]	Policy [c]				
	Ban et al. (2017) [80]	○	○	-	Information of the PV panels/inverters/region, roof's properties	Mathematical method RETScreen	Korea	• Based on the point of view of NPV and SIR, the optimal rooftop PV system type was analyzed for three regions (i.e., northern part, middle part, and southern part) in South Korea.
	Elibol et al. (2017) [81]	○	-	-	PV panel type (e.g., mono-crystalline and polycrystalline), amount of radiation, panel temperature	Experiment, statistical analysis	Turkey	• The efficiency of PV panel was 4.79, 11.36, and 13.26% in the order of a-Si, polycrystalline, and monocrystalline PV panel • The external temperature was correlated positively with a-Si and polycrystalline PV panel, and negatively correlated with monocrystalline PV panel
	Hong et al. (2017) [82]	○	-	-	Building data, region (e.g., altitude), shaded area, fixed-tilt system, tracker system	Mathematical method, Vworld	Korea	• As a result of applying the developed methodology to Gangnam district, Seoul, South Korea, the physical, geographic, and technical potentials of Gangnam district were 9,178,982 MWh, 4,964,118 m^2, and 1,130,371 MWh

Table 7. *Cont.*

Classification	Research	Analysis Target			Design Variables	Simulation Tool or Method	Country	Main Findings
		Technical [a]	Economic [b]	Policy [c]				
Building-integrated PV system (Vertical)	Lu and Yang (2010) [83]	○	○	-	Weather data, solar radiation, orientation, inclined angle of PV	Mathematical method, LCA	Hong Kong (China)	• The lifespan of a roof-mounted 22 kW BIPV system in Hong Kong is 20–30 years
	Radhi (2010) [84]	○	-	-	Regional factors, design, and performance of BIPV system	MeteoNorm software, Energy-10 software	UAE	• The optimal tilt angle is 24° • When the angle of the PV is 90° in the western PV façade generates more output than in the southern façade
	Hong et al. (2011) [85]	○	○	-	Energy consumption, energy consumption/per occupant	Mathematical method	Korea	• Proposed alternatives installed the renewable energy system can reduce the electricity consumption about 18%
Building-integrated PV system (Vertical)	Hammond et al. (2012) [86]	○	○	○	PV installation/electricity cost, financial support policy	Eco-indicator 99, Mathematical method	UK	• UK households that consume average power can save 240 kW, £29 a year through installation of BIPV
	Hwang et al. (2012) [87]	○	-	-	Weather data, building information, details of PV panels	Building management system of Samsung, CAD, Equest	Korea	• A horizontally inclined angle of 60° and a vertically inclined angle that is smaller than 15° is efficient for generation. • Set the distance between panels/length of panel ratio between 1 and 3 is cost effective
	Chae et al. (2014) [88]	○	○	-	*U*-factor, solar heat gain coefficient, visible transmittance, source energy unit price	Mathematical method, EnergyPlus	Korea	• The performance of BIPV window is affected by several variables (e.g., utility cost, thermal optical characteristics of window system)

Table 7. *Cont.*

Classification	Research	Analysis Target			Design Variables	Simulation Tool or Method	Country	Main Findings
		Technical [a]	Economic [b]	Policy [c]				
	Lee et al. (2014) [89]	○	-	-	PV panel's efficiency, building load	Mathematical method	Korea	• The performance of BIPV can be affected by various causes (e.g., thermal destruction of the thin-film PV system and reduction of efficiency by installation of inverters)
	Olivieri et al. (2014) [90]	○	○	-	Glazing properties, climate data, building information	DeignBuilder, EnergyPlus, PVSyst, COMFEN	Spain	• Depending on the size of façade opening, semi-transparent PV solution has energy saving potential of 18 to 59% compared to reference glass
	Park et al. (2016) [91]	○	○	○	Region, visible transmittance, exterior window area, window-to-PV panel ratio, PV panel's efficiency	Finite element method, Microsoft excel based VBA	Korea	• This study developed a model for estimating the amount of electricity generated from distributed solar generation based on the four-node based Lagrangian finite element method • Through the developed model, users can conduct economic evaluation considering grid-connect and self-consumption utilization plans
	Peng et al. (2016) [92]	○	-	-	Semi-transparent PV's properties, infrared thermal emissivity and thermal conductivity	EnergyPlus, mathematical model, sensitivity analysis	USA	• Predicted energy performance according to the window installation's type and compare with commonly used window technology
	Hong et al. (2017) [93]	○	○	○	Architectural design variables, window design variables, building-integrated PV blind (BIPB) design variables	Autodesk Ecotect Analysis, mathematical method	Korea	• The width of the PV panel increases, the amount of electricity generated from the BIPB per unit area and SIR_{25} tends to decrease, but NPV_{25} tends to increase

Table 7. *Cont.*

Classification	Research	Analysis Target			Design Variables	Simulation Tool or Method	Country	Main Findings
		Technical [a]	Economic [b]	Policy [c]				
	Koo et al. (2017) [94]		○	○	Type of PV panel/tracking system, building data	RETScreen, ArcMap 10.3, mathematical method	Korea	• Through the techno-economic-policy analysis, $SPSB_{CIGS\&2\text{-}axis}$ (i.e., SPSB with the CIGS PV panel and the two-axis tracking system) is the best installation type from each point of view
	Oh et al. (2017) [95]	○	○	○	Electricity rate in South Korea, region, orientation, visible transmittance, PV panel efficiency, wall and window area, WWR, window-to-PV panel ratio	Finite element method, Microsoft excel based VBA	Korea	• The $FEM_{9\text{-}node}$ method is developed to estimate the generation of BIPB • The impact of residential progressive electricity tariff in economic performance was analyzed

Note: "○" means that the study was performed the upper analysis target (i.e., technical, economic, and policy). "-" means that the study was performed the upper analysis target (i.e., technical, economic, and policy). [a] *Technical* means that the analysis target is technical performance; [b] *Economic* means that the analysis target is economic performance; and [c] *Policy* means that the analysis target is economic performance according to various policies.

Table 8. Literature review on the solar thermal system in terms of renewable energy.

Research	Analysis Target		Design Variables	Simulation Tool or Method	Country	Main Findings
	Technical [a]	Economic [b]				
Anderson et al. (2010) [96]	○	-	Color of building integrated solar collector	Mathematical method	New Zealand	• Low-cost colored mild steel collectors could contribute to water heating load, despite low efficiency
Mammoli et al. (2010) [97]	○	○	Solar flux, flow rate and input/output, solar collector's efficiency, absorption chiller's performance, heating/cooling system operation time	TRNSYS	Mexico	• During the summer, the solar cooling system can supply about 18% of the total cooling load, but can increase the efficiency to 36% by changing the system operation.

Table 8. *Cont.*

Research	Analysis Target		Design Variables	Simulation Tool or Method	Country	Main Findings
	Technical [a]	Economic [b]				
Ampatzi and Knight (2012) [98]	○	-	Building information, weather data, infiltration/ventilation rates, internal gains, hot water consumption	TRNSYS, TRNbuild, ECOTECH	Wales (UK)	• Lighting and plug loads should be taken into account when designing STE system because they affect the heating and cooling requirements for all generations and types.
Bornatico et al. (2012) [99]	○	-	Meteorological data, collector area, tank volume, auxiliary power unit size	MATLAB, Polysun, PSO algorithm, mathematical method	Switzerland	• The size of the collector has a significant impact on energy use and installation costs, but the size of the APU does not have a significant effect.
Fong and Alwan (2013) [100]	○	-	Weather data, cooling profile	TRNSYS, IES, mathematical method	UK	• Solar powered desiccant cooling is more suited to buildings because it has a high cooling efficiency and high carbon reduction potential.
Motte et al. (2013) [101]	○	-	Solar irradiance, ambient temperature, wind speed, input/output water temperature	Mathematical method, MATLAB	France	• Comparing the experimental and simulation results, the RMSE was 5% for temperatures water and 4.6–10% for the internal temperature.
Lamnatou et al. (2014) [102]	○	-	Characteristic of the building integrated solar thermal system, life cycle inventory	Mathematical method	France	• If you using recycling with system 2 (i.e., collectors of parallel connection/tubes at different levels), the energy payback time can decrease to 0.5 years
Li et al. (2014) [103]	○	-	Operation control parameters, storage characteristics, matching degree between solar collector area and system integral capacity	TRNSYS, mathematical method	China	• Research has shown that the system (i.e., combined solar thermal heat pump with heating system for supplying space heating and domestic hot water in cold climate) is more beneficial in terms of energy and environmental aspects
Maurer et al. (2015) [104]	○	-	U-value , ambient temperature, room temperature, zero-g-value	Mathematical method	-	• Four simple models (e.g., adaptation of the efficiency curve/collector result) are developed

Table 8. *Cont.*

Research	Analysis Target		Design Variables	Simulation Tool or Method	Country	Main Findings
	Technical [a]	Economic [b]				
Kim et al. (2016) [105]	○	-	Region, azimuth/slope/type of collector, storage type, rooftop area, minimum heat generation limit, maximum budget limit	Mathematical method, Microsoft Excel based VBA	Korea	• The integrated multi-objective optimization (iMOO) model can help the user decide the optimal solution for the installation of the solar thermal system in the early design phase.
Araya et al. (2017) [106]	○	○	Solar flat-plate collector arrangement, water tank, auxiliary system, energy demand	Genetic algorithms, MATLAB, LCC	Chile	• This study found the optimal combination of collector area and storage volume
Chialastri and Isaacson (2017) [107]	○	○	Glazing type (e.g., uncoated, Low-e double), material (e.g., aluminum), air speed, temperature	Experiment, two-dimensional model in COMSOL Multiphysics	USA	• A prototype of a building-integrated PV/thermal air collector was tested under different conditions • The maximum temperature of the prototype was 31°C, and the average thermal and electrical efficiencies were 31% and 7%, respectively

Note: [a] *Technical* means that the analysis target is technical performance; and [b] *Economic* means that the analysis target is economic performance.

Table 9. Literature review on the geothermal system in terms of renewable energy.

Research	Analysis Target		Design Variables	Simulation Tool or Method	Country	Main Findings
	Technical [a]	Economic [b]				
Wood et al. (2010) [108]	○	-	Date, average air temperature, season	EED, GLHEPRO, Mathematical method	UK	• At a point of 2.5 m distance, the ground temperature increased by 1°C. It gets bigger in the neighborhood of 1 m, the ground temperature increased by 2.5° in excess of the seasonal change

Table 9. *Cont.*

Research	Analysis Target		Design Variables	Simulation Tool or Method	Country	Main Findings
	Technical [a]	Economic [b]				
Desideri et al. (2011) [109]	○	-	Design of underground heat exchangers, soil type, number/total length/distance between the boreholes, energy demand, heating/cooling plant installation cost	TRNSYS 16	Italy	• Ground source heat pump (GSHP) systems show economic and environmental benefits by reducing operating costs and CO_2 emissions per year
Kim et al. (2012) [110]	○	○	Heat pump type (e.g., inverter type), outdoor/indoor temperature, relative humidity	Experiment	Korea	• The GSHP's coefficient of performance (COP) was 6.0 to 10.9 depending on the load conditions and it can reduce the average electricity consumption of 44.1 kWh per day
Sivasakthivel et al. (2012) [111]	○	○	Region (e.g., several/moderate cold), COP of GSHP	Mathematical method	India	• As the COP increased from 2 to 3, the electricity consumption and the discharge of CO_2 were decreased by about 25% • The GSHP system is more efficient in cold areas
Kang et al. (2013) [112]	○	-	Season, climate weather data	Mathematical method, MATLAB/Simulink	France, Korea	• The newly developed hybrid model for assessing the geothermal system's seasonal performance is about 1% better than the original model in terms of estimation accuracy
Self et al. (2013) [113]	○	○	Variable of geothermal heat pump	-	Europe	• Heat pumps utilize significantly less energy to heat a building than alternative heating system
Morrone et al. (2014) [114]	○	○	Ground characteristic, building information, performance of heat pump/cooling machine, loading conditions for heating and cooling	Mathematical method, DOCET, PILESIM2	Italy	• In cold climates, the rise of the ground temperature by GSHP is negligible, and even in the worst case, primary energy saving is at least 10%
Kim et al. (2015) [115]	○	○	Region, geothermal heat exchanger properties, heating/cooling loads, entering water temperature	Mathematical method, LCI & LCC Analysis, GLHEPro	Korea	• In summer time, the temperature of input water entering to the heat pump is decreased, increasing the efficiency of the GSHP and increasing the length of the borehole

Table 9. *Cont.*

Research	Analysis Target		Design Variables	Simulation Tool or Method	Country	Main Findings
	Technical [a]	Economic [b]				
Kharseh et al. (2015) [116]	○	○	Building/GSHP specification, driving energy of A/C system	Earth energy designer, HAP	Qatar	• Calculation of the required borehole length was computed based on the cooling loads, cooling capacity, and the area of the building, and calculated the internal yield of GSHP
Lee et al. (2015) [117]	○	○	Specifications of the vertical/horizontal GCHE, outdoor temperature, electric power, energy consumption	TRNSYS	Korea	• The vertical GCHE uses less power than the horizontal GCHE and has a greater energy savings potential from a long-term perspective
Hong et al. (2016) [118]	○	-	Borehole length/spacing/diameter, grout thermal conductivity, U-pipe diameter/spacing	Mathematical method, GLHEPro	Korea	• The borehole length is the most influential factor in energy and environmental aspects
Jeong et al. (2017) [119]	○	-	Geographic, annual average temperature, annual heating days, ground heat exchanger's characteristics, threshold fluid temperature	FEM, G.POT, Kriging method	Korea	• The newly developed hybrid model was about 1% better than the original model

Note: [a] *Technical* means that the analysis target is technical performance; and [b] *Economic* means that the analysis target is economic performance.

Table 10. Literature review on the wind turbine system in terms of renewable energy.

Research	Input Data	Output Data	Simulation Tool or Method	Country	Main Findings
Sharpe and Proven (2010) [120]	Blade design, pitch control/angle, pitch control of rotor rpm	Development of true building integrated wind turbine	Stream tube model, Mathematical method, μ-wind	UK	• Blade pitch affects the overall performance of the turbine • Cowling can improve other characteristics
Walker (2011) [121]	Wind speed, theoretical power curves, turbine performance	Measurement of power production	Mathematical method, CFD, BREV-e	UK	• Power curve provided by the turbine manufacturer is not accurate in low or high wind speeds • Simplified power curve for estimating the energy generation is not appropriate for all turbine system

Table 10. *Cont.*

Research	Input Data	Output Data	Simulation Tool or Method	Country	Main Findings
Ayhan and Sağlam (2012) [122]	Geometry scenarios and building layout, assembly forms to the building of wind turbines	Feasibility of wind power utilization	CFD, mathematical method	Turkey	• Wind tunnels in urban areas are better positioned than rural areas
Balduzzi et al. (2012) [123]	Wind turbine's characteristics, city data (e.g., building height)	Flow velocity modulus and direction, attended capacity factor, new turbine model	CFD, Reynolds-averaged Navier–Stokes (RANS)	Europe	• The performance of the Darrieus turbine was optimized when the height was higher than the surrounding structure, the roof inclination angle was 8 degrees, and the slope was 25°.
Li et al. (2013) [124]	Wind tunnel tests, wind climate data analysis	Wind loads on tall buildings, wind speed up factors in the tunnels for wind-power generation	Mathematical method, real model test	China	• The buildings located near the target building affect the amplification of wind speed and wind loads on tall buildings • A large opening ratio interrupt the wind energy and force.
Lu and Sun (2014) [125]	Wind/building data	Wind power utilization into or on urban high-rise buildings	CFD, ANSYS/FLUENT, UDF	Hong Kong (China)	• The best place to install a wind turbine is 3.6 m above the windward side top corner
Park et al. (2014) [126]	Region, building information, characteristic of small wind power generation system	Noise and vibration, amount of power generated by the small wind power system	CFD, mock-up test	Korea	• Wind power with high on the side, and circular or triangular forms are advantageous for wind power generation.
Yang et al. (2016) [127]	Climate data, wind velocity and direction, turbulence intensity, complex urban topography of the studied site	Maximum power density with optimum height	ANSYS/Fluent, SIMPLEC, CFD, RANS	Taiwan	• For higher wind power production, it is necessary to increase the hub height and located the micro turbines on the wind road.
Cao et al. (2017) [128]	Building information, wind data, heights of the first five layers in the meteorological data	Annual average power output/electric power yield of building integrated wind turbine system	Mathematical method, CFD, WRF Model	China	• Wind speeds are strongest at 300 m, and they steadily decreased as the height increases beyond that, and rises slightly when it rises beyond 800 m.

2.2.2. Part B-2: Back-Up Systems for RE

In this study, from the perspective of the implementation of nZEB, the previous studies related to the back-up systems for the effective application and management of RE focused on the following two types: (i) fuel cell system; and (ii) energy storage system (ESS). Also, this study summarized the various previous studies related to the back-up system in Tables 11 and 12.

(1) Fuel cell system: The fuel cell system is an electricity power generator that utilizes electricity produced through the chemical reaction of hydrogen and oxygen. Furthermore, the fuel cell system can be more effectively used when applied with RE. This is because the electricity produced from RE can be used in the electrolysis of water in the fuel cell system [129]. The previous studies related to the fuel cell system are as follows (refer to Table 11) [130–135]. Hong et al. (2014) aimed to develop a framework for optimally applying the fuel-cell-based combined heat and power system to a multi-family housing complex. Also, in order to verify the feasibility of developed framework, this study evaluated the fuel-cell-based heat-and-power-combined system for 'O' apartment in Seoul, South Korea from the perspectives of primary energy savings, life cycle cost, and life cycle CO_2 [130]. Ansong et al. (2017) conducted a techno-economic performance analysis of the hybrid electric power system (i.e., PV system, fuel cell system, and diesel generator) for an off-grid mine company using the HOMER software program to select the optimal energy system. As a result, it was shown that the optimal electric power system could produce 152.99 GWh electricity over a year when composed of 50 MW of PV system, 15 MW of fuel cell system, and 20 MW of diesel generator [135].

(2) ESS: RE is heavily affected by electricity generation based on the outdoor environment conditions (e.g., solar radiation, wind strength, etc.). To solve this problem, various studies are being conducted on the ESS as a back-up system that can store the electricity generated from the RE. In this study, the previous studies related to ESS are classified into those on the thermal ESS and those on the electrical ESS depending on the type of stored energy (refer to Table 12) [136–142]. First, the previous studies conducted in terms of thermal ESS are as follows [136–139]. Alimohammadisagvand et al. (2016) aimed to find a cost-optimal solution for thermal ESS integrated with the geothermal system for a residential building in a cold climate based on the concept of demand response (DR) (i.e., a momentary DR control based on the real-time hourly electricity price, a backwards-looking DR control based on the previous hourly electricity price, and a predictive DR control based on future hourly electricity price). The analysis result showed that applying the predictive DR control algorithm is most effective in terms of the annual savings in the total delivered energy and cost [136]. Al Zahrani and Dincer (2016) conducted a performance evaluation of the aquifer thermal ESS considering the charging temperature, storing time, temperature during storing, discharging temperature, etc. To this end, this study analyzed focusing on the energy and exergy during the heating and cooling period using the Engineering Equation Solver software program [137]. Second, the previous studies that were conducted in terms of the electrical ESS are as follows [140–142]. Vieira et al. (2017) considered the ESS connected with the PV system of a residential building as a system for matching the energy production and consumption in Coimbra, Portugal. The results indicated that the ESS connected with the PV system can reduce the energy sent to and consumed from grid by 76 and 78.3%, respectively, as well as the energy bill by 87.2% [142].

(3) Discussion: In this study, studies regarding the back-up system were analyzed focusing on the fuel cell system and ESS in terms of effective operation of the RE. First, from the perspective of the fuel cell system, the techno-economic performance analysis was conducted mainly based on simulation tools. Second, from the perspective of the ESS, various studies are underway so as to analyze the technical and economic effects based on DR strategies combined with RE. In terms of the back-up system, especially for ESS-related research, it is considered to be more effective in terms of energy savings because DR strategies are applied so as to analyze the technical

performance by considering energy demand and supply. However, there will be limitations in obtaining optimal techno-economic effects because existing studies related to this are based on historical data (e.g., monthly or yearly data) rather than real-time data.

Table 11. Literature review on the fuel cell system in terms of back-up system for renewable energy.

Research	Analysis Target		Design Variables	Simulation Tool or Method	Country	Main Findings
	Technical [a]	Economic [b]				
Hong et al. (2014) [130]	○	○	Fuel cell combined heat and power system's operating scheme and size, energy demand/supply	Mathematical method, Crystal Ball	Korea	• IS_PLF_500kW, an implementation strategy with the operating scheme of power load following and the operating size of 500 kW, is determined as an optimal strategy in terms of primary energy saving • IS_HLF_200kW, an implementation strategy with operating scheme of heating load following and operating size of 200 kW, is determined optimal strategy in terms of LCC & $LCCO_2$
Adam et al. (2015) [131]	○	-	Building information, region, occupancy schedule	IES VE, Mathematical method	UK	• Fuel cell micro-CHP can save considerable energy and cost when properly used in residential
Kim et al. (2014) [132]	○	○	Building type, operating scheme, operating size, energy demand/supply	Mathematical method, Microsoft-Excel-based VBA	Korea	• In case of multi housing family complex, the optimal operating strategy is IS_HLF_200kW (i.e., an implementation strategy with the operating scheme of heating load following and the operating size of 200 kW)
Sossan et al. (2014) [133]	○	○	Building indoor temperature, fuel cell and tank's properties, optimization horizon length, maximum fuel cell off–on cycles	CTSM, LabView, mathematical method	-	• New proton exchange membrane fuel cell model suitable for smart grid and micro-grid applications is presented and this model can increase to 25% efficiency by efficiently using different energy resources
Elmer et al. (2016) [134]	○	○	Tri-generation system energetic performance	Mathematical method	UK	• The performance of solid oxide fuel cell varies from country to country, but high performance can be achieved if the solid oxide fuel cell contains a liquid desiccant.
Ansong et al. (2017) [135]	○	○	Site location, electrical load, solar resource, diesel fuel's information	HOMER software	Ghana	• It is shown that the optimal electric power system can produce 152.99 GWh electricity over a year when composed of a 50 MW PV system, a 15 MW fuel cell system, and a 20 MW diesel generator

Note: [a] *Technical* means that the analysis target is technical performance; and [b] *Economic* means that the analysis target is economic performance.

Table 12. Literature review on the energy storage system in terms of back-up system for renewable energy.

Classification	Research	Analysis Target		Input Data	Simulation Tool or Method	Country	Main Findings
		Technical [a]	Economic [b]				
Thermal energy storage system	Alimohammadisagvand et al. (2016) [136]	○	○	Indoor/storage tank temperature set point, hourly electricity price, weather, building information, HVAC system	IDA ICE, Monte-Carlo simulation, NIDAQ	Finland	• The maximum energy and cost savings were 12% and 10%, when compared to buildings without demand response control and storage capacity
	Al Zahrani and Dincer (2016) [137]	○	-	Dis/charging temperature, mass flow rate, storing time, temperature drop/rise during storing, ambient temperature	Mathematical method, EES	Canada	• The performance of aquifer thermal energy storage is strongly influenced by the heat loss and gain during the energy storage period
	Jin et al. (2017) [138]	○	○	External walls and windows' heat transfer, internal heat gains, heat contribution, solar radiation, cooling power generated	Mathematical method	USA	• The performance of virtual energy storage system is closely connected to the buildings' occupied hours, buildings' parameter, and time sensitive electricity prices
	Jradi et al. (2017) [139]	○	○	Monthly global solar irradiation in Odense and PV system yield, heating energy satisfied by PV-driven heat pump, electrical energy demand/supply	Mathematical method, MATLAB	Denmark	• An air source heat pump is used to store excess power in soil storage media in summer
Electrical energy storage system	Connolly et al. (2012) [140]	○	○	Electricity demands, energy storage system's capacities/efficiencies, regulation strategies, fuel cost, distribution data (e.g., heat, electric)	Energy PLAN, mathematical method	Ireland	• If using pumped hydroelectric energy storage system and wind power generation can reduce the operation cost
	Ma et al. (2015) [141]	○	-	The presence or absence of supercapacitor	MATLAB/Simulink, mathematical method	-	• Hybrid energy storage system has proven that it can stabilize the energy supply for fluctuating loads as well as intermittent renewable energy
	Vieira et al. (2017) [142]	○	-	Solar radiation, energy consumption, PV panel, and battery information	MATLAB/Simulink, mathematical method, PVSyst	Portugal	• Simulation results show that 76% of the energy send and 78.3% of the energy consumed are reduced by the grid, and 87.2% reduction in annual energy costs

Note: [a] *Technical* means that the analysis target is technical performance; and [b] *Economic* means that the analysis target is economic performance.

3. Future Directions and Challenges for Realizing nZEB

Through the extensive literature review conducted in Section 2, this study identified that the various studies related to active and passive strategies for implementing nZEB proceeded from the following perspectives: (i) passive strategies: passive sustainable design (i.e., building geometry, natural lighting, and natural ventilation) and EST (i.e., building envelope design, heat storage system, and lighting system) ; and (ii) active strategies: RE (i.e., PV system, solar thermal system, geothermal system, and wind turbine system) and back-up system for RE (i.e., fuel-cell system and ESS). In addition, this study presented several advanced strategies that could be implemented for realizing nZEB in terms of the following two perspectives focused on the maintenance stage from the planning stage (i.e., (a) and (b) in Figure 2), where the potential for energy-saving and CO_2 emission reduction is high: (i) integration and optimization of the passive and active strategies in the early phase of a building's life cycle; and (ii) real-time monitoring of the energy performance during the usage phase of a building's life cycle [143,144].

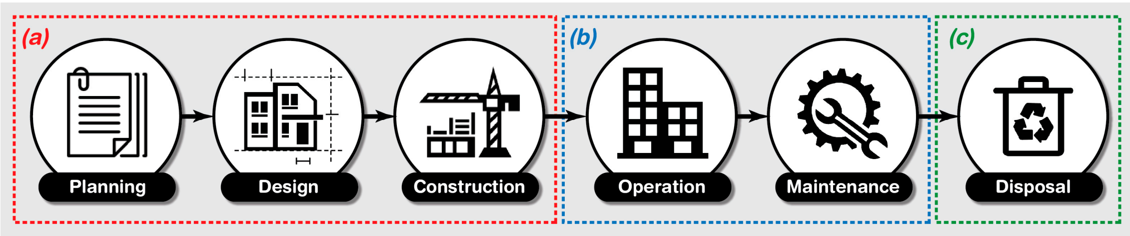

Figure 2. Building's life cycle: (**a**) stands for the early phase of a building's life cycle; (**b**) stands for the usage phase of a building's life cycle; and (**c**) stands for the disposal phase of a building's life cycle.

3.1. Integration and Optimization of the Passive and Active Strategies in the Early Phase of a Building's Life Cycle

In stage (a) of Figure 2, it is necessary to integrate the passive and active strategies and to provide an optimized design solution for nZEB implementation. Therefore, in this study, advanced strategies for implementing nZEB are presented from the following two perspectives: (i) integration of the passive and active technologies; and (ii) optimization of the passive and active strategies for determining the optimal design solution.

3.1.1. Integration of the Passive and Active Strategies

Basically, to realize nZEB, passive strategies (i.e., passive sustainable design and ETS) and active strategies (i.e., RE and back-up system) should be applied sequentially to a building. In other words, a two-step process consisting of the step of reducing the building energy demand based on the passive technologies (e.g., natural ventilation, heat storage system, etc.) and the step of substituting the residual building energy demand through energy supply from active technologies (e.g., PV system with ESS) must be adopted. Most of the previous studies, however, were conducted by focusing on only one strategy (i.e., passive or active strategies) [8–38,40–128,130–142]. Therefore, an integrated analysis of the energy performance of a building where both passive and active strategies are applied should be performed in the early phase of a building's life cycle from the perspective of achieving nZEB. For example, McDonald and Chakradhar (2017) proposed a design plan that could realize an energy-efficient building by reducing the energy consumption and applying the optimal RE through an extensive analysis of the monthly climate data, passive strategies (e.g., passive solar techniques, solar shading, etc.), and site elements of Kathmandu, the capital city of Nepal. This study showed that applying passive and active strategies in the early stages of a building's life cycle (i.e., stage (a) in Figure 2) is very important in terms of the CO_2 emission reduction of the building [145]. Wang et al. (2009) investigated the feasibility of zero energy houses in the UK via energy simulation programs by considering the RE and façade design. From this study, it can be found that zero energy homes in the UK could be realized through the introduction of the PV system, wind turbine system, and optimal façade design (i.e., south facing, 0.4 WWR on the south façade, 0.1 or less WWR on the other oriented facades, and 0.1 U-value for external walls and roof) [146]. As a result, the integration of the passive and active strategies is an essential challenge for the implementation of nZEB, beyond an energy efficient building.

3.1.2. Optimization of the Passive and Active Strategies for Determining the Optimal Design Solution

To integrate the passive and active strategies effectively, it is essential to develop an optimization model for determining the optimal solution by considering the design variables based on the analysis results on the techno-economic performance of a building (e.g., energy demand such as the heating and cooling load, energy supply such as the amount of electricity generated from the PV system, net present value (NPV), saving-to-investment ratio (SIR), and payback period (PP)) in the early stage of a building's life cycle. There are various previous studies regarding the estimation and optimization of techno-economic performance of a building considering the design variables, but the methodologies that were used by such studies have limitations in the following three aspects: (i) application stage; (ii) user; and (iii) analysis target. First, in terms of application stage, as the existing methodologies require specific building information, there are restrictions to their use in the early stage of a building's life cycle. Second, to conduct the estimation and optimization of the building energy supply and demand using any of the existing methodologies, energy simulation tools or complex calculations and other professional knowledge are required. It is difficult, however, for non-experts like the construction manager (CMr) and designers to perform energy simulation tools or complex calculations. Finally, most of the previous relevant studies were conducted by considering only one aspect of building energy demand and supply, and as such, there are restrictions to deriving an optimal solution that considers both building energy demand and supply in terms of implementing nZEB [78,147–152]. Therefore, this study proposes an optimization model that could overcome the limitations of the previous relevant studies from the viewpoint of nZEB implementation through the following two stages: step 1: development of an integrated analysis model for estimating the building energy demand and supply; and step 2: development of an integrated multi-objective optimization model for determining the optimal design the solution for the realization of nZEB.

(1) Step 1—Development of an integrated analysis model for estimating the building energy demand and supply: Those who want to implement nZEB (e.g., CMr and designer) should be able to easily and quickly analyze the building energy demand and supply for the application of the passive and active strategies at the early phase of a building's life cycle. An examination of the previous studies in this regard revealed that Koo et al. (2014) and Park et al. (2016) developed an estimation model for the building energy demand (i.e., heating and cooling demand) and supply (i.e., the amount of electricity generated from the distributed solar generation system) based on four-node-based Lagrangian shape function that is easy to use during the early design phase (refer to Figures 3, A1 and A2). These studies, however, also have limitations in evaluating the energy performance in terms of nZEB because the energy demand and supply were analyzed separately according to the building envelope design [39,91]. Therefore, developing an integrated-analysis model of energy demand and supply for applying the active and passive strategies' technology in the early stage of a building's life cycle remains a top-priority challenge for implementing nZEB as shown in Figure 4.

(2) Step 2—Development of an integrated multi-objective optimization (iMOO) model for determining the optimal design solution for the realization of nZEB: In the early stage of a building's life cycle, the CMr and designer should take into account not only the building's energy demand and supply, but also the building's economic performance (e.g., NPV, SIR, and PP) depending on the design conditions (e.g., WWR, window type, window-to-PV panel ratio, etc.). As these considerations, however, have a trade-off relationship, it is very difficult for the

CMr and designer to decide the optimal design plan by incorporating all the considerations at the initial stage of a building's life cycle [105,153]. Therefore, it is necessary to develop an iMOO model to help in the CMr and designer's decision-making and can implement a reasonable nZEB. In the previous studies, several methodologies have been developed to address the trade-off relationship between the building energy performance (e.g., energy demand and supply) and the building's economic performance (e.g., NPV, SIR, and PP). Koo et al. (2015) proposed an iMOO model based on the concept of the Pareto front, which can provide the optimal design solution to the users by solving the trade-off problems between the construction time and cost, according to the following six processes: (i) problem statement; (ii) definition of the optimization objectives; (iii) establishment of the data structure; (iv) standardization of the optimization objective function; (v) definition of the fitness function; and (vi) implementation of the genetic algorithm (refer to Figure 5) [154]. In addition, based on this paper, Koo et al. (2016) and Kim et al. (2016) developed an iMOO model for determining the optimal solution in implementing RE, considering the techno-economic performance (refer to Figure A3) [105,153]. The iMOO model suggested in the aforementioned studies has the advantages of solving the trade-off problems between various optimization objectives (i.e., energy demand or supply, NPV, SIR, and PP) and deriving the optimal solution in a user-friendly design. When deriving the optimal design solution, however, the aforementioned studies had limitations in that they did not consider the building energy demand and supply simultaneously. In other words, from the standpoint of the effective implementation of nZEB, the iMOO model must be achieve in the direction of minimizing the building energy demand (e.g., heating and cooling demand) and optimizing the energy supply (e.g., the amount of electricity generated from PV system) and economic performance (e.g., NPV, SIR, and PP). Therefore, from the viewpoint of the integration of the passive and active strategies to implement nZEB, the development of the iMOO model considering the both energy demand and supply remains a challenge for many researchers (refer to Figure 6).

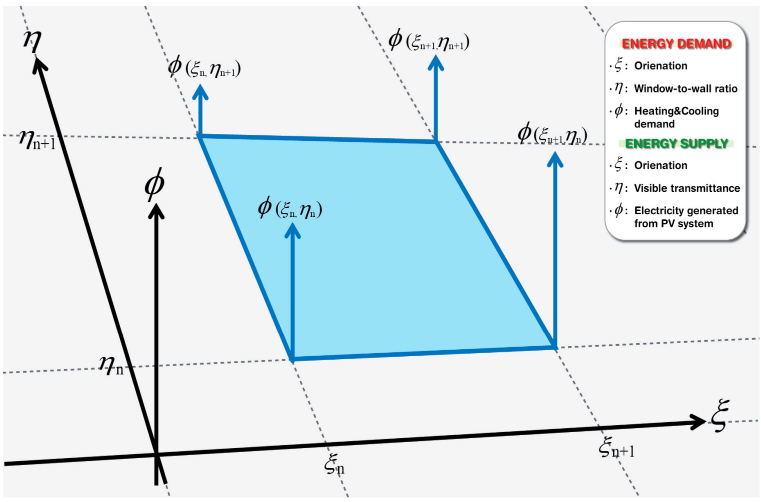

Figure 3. Concept of four-node based Lagrangian shape function.

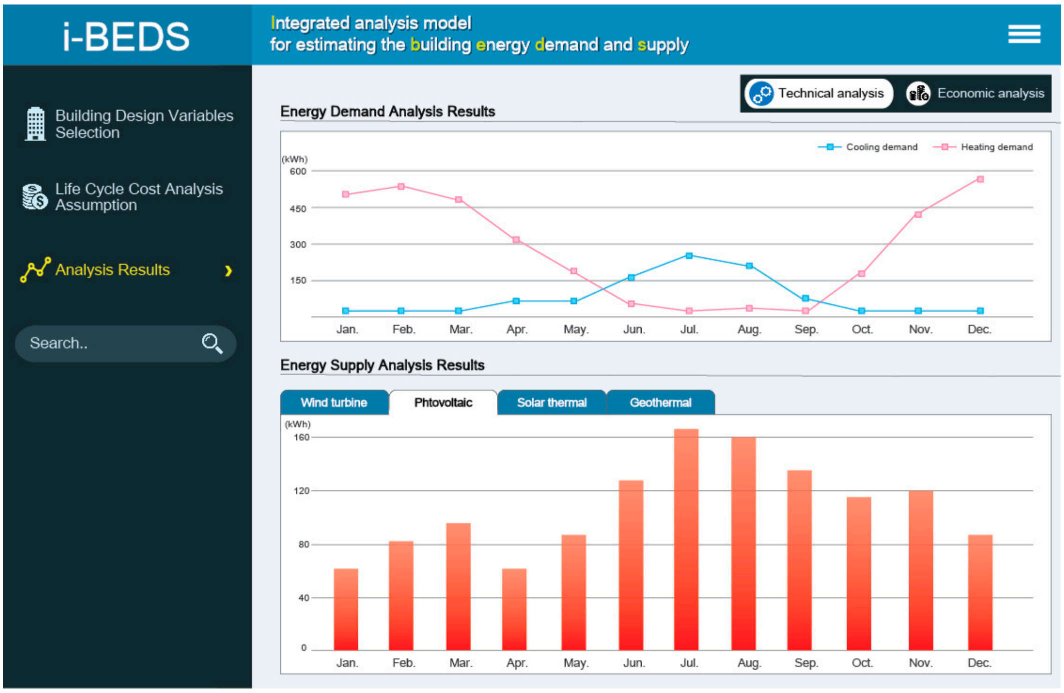

Figure 4. Graphical user interface for integrated analysis model for estimating the building energy demand and supply.

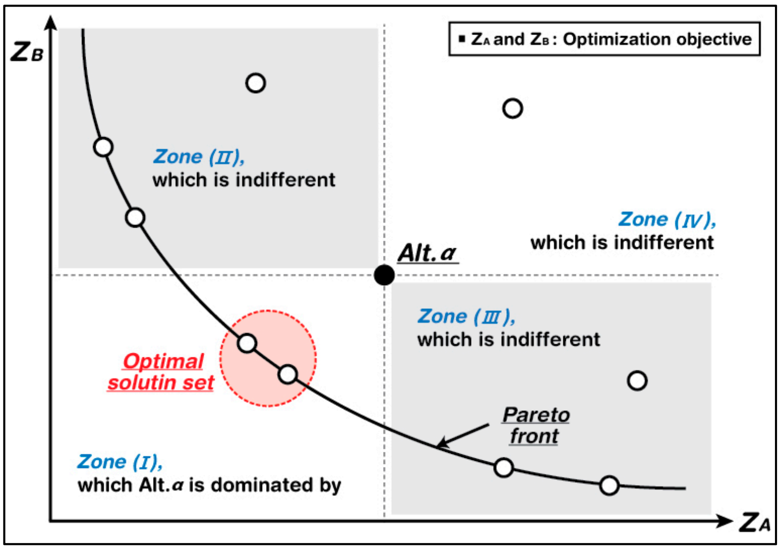

Figure 5. The concept of the Pareto front and the optimal solution set.

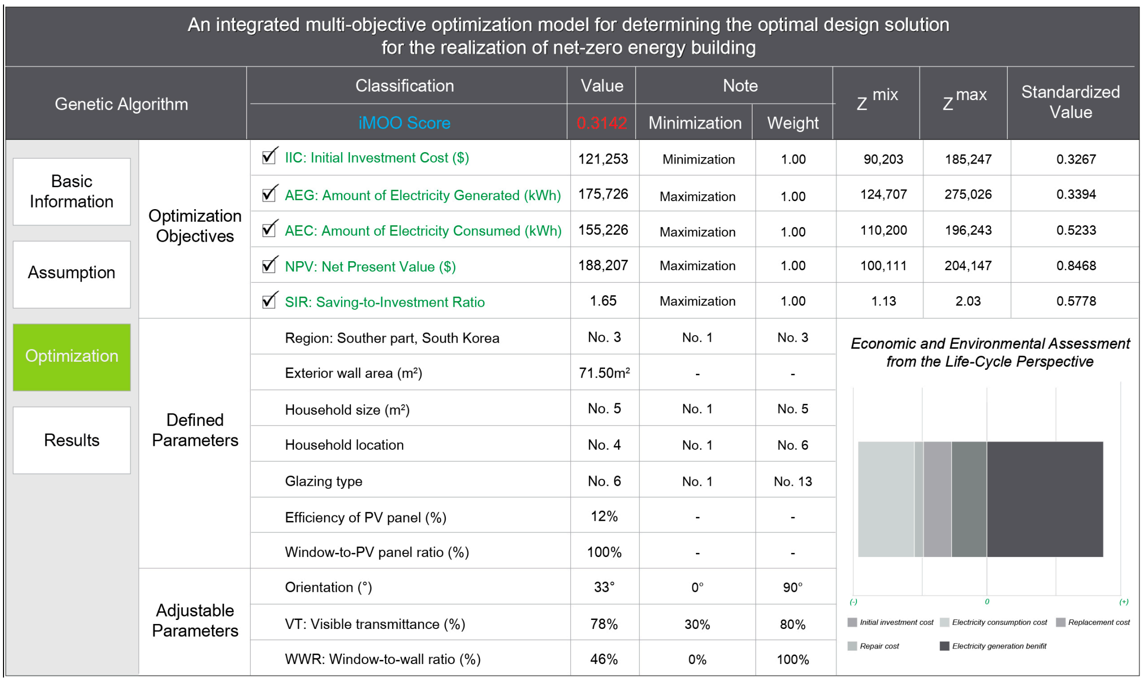

Figure 6. Graphical user interface for an integrated multi-objective optimization (iMOO) model for determining the optimal design solution for the realization of nZEB.

3.2. Real-Time Monitoring of the Energy Performance during the Usage Phase of a Building's Life Cycle

As shown in Figure 7, the optimal strategy for implementing nZEB is to construct a building with minimal energy demand by applying optimal strategies combining the passive and active strategies in the early stage of a building's life cycle, and to efficiently manage the building via real-time energy monitoring in the usage stage. In other words, the energy demand and supply should be controlled effectively based on real-time monitoring of the building energy performance for implementing the nZEB during the building usage phase (i.e., stage (b) in Figure 2). In this study, strategies for realizing nZEB through real-time monitoring at the building usage stage are presented from the following two perspectives: (i) developing an integrated real-time monitoring system for the building energy performance; and (ii) analyzing the energy-saving potential through the end user behaviors.

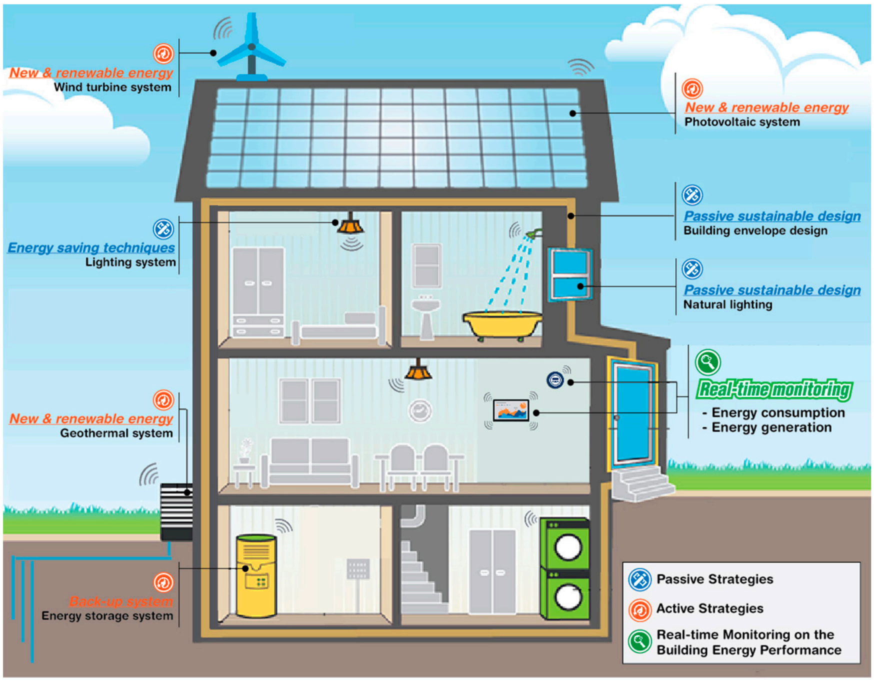

Figure 7. Concept of the optimal strategy for implementing nZEB.

3.2.1. Developing an Integrated Real-Time Monitoring System for Building Energy Performance

In the previous studies analyzed in Section 2.2.2, most applied DR to analyze energy savings based on historical data [130–142]. However, in order to effectively manage the building from nZEB perspectives, it is necessary to obtain the energy demands and supply information in real-time. Therefore, it is very important to develop a real-time monitoring system for the building energy performance as shown in Chou et al. (2017) which developed a web-based application that could induce energy-saving in an office building through an early warning system for the occupants based on the R data mining application, the Apache web server, JavaScript, the RazorFlow dashboard framework, etc. [155–157]. In addition, a more detailed monitoring system is needed due to the diversity of buildings as well as the zones, rooms, and devices inside the building. In other words, the cause of the low energy efficiency of a building cannot be analyzed concretely if real-time monitoring of the energy consumption and generation is done across the entire building. Therefore, during the usage stage of building, it will be necessary to realize a detailed integrated real-time monitoring system in terms of the zone, room, and devices inside the building, in addition to real-time monitoring for the entire building, so as to better analyze the specific causes of the low energy efficiency of the building and to effectively manage the building (refer to Figure 8).

Figure 8. Integrated real-time monitoring system for the building energy performance.

3.2.2. Analyzing the Energy-Saving Potential through the End-User Behaviors

There is growing interest in DR as a way to mitigate the crises in the electricity supply and demand (e.g., large-scale black out) and to maintain the electricity supply-demand balance. The DR strategies currently being implemented are mainly divided into cost-based DR (e.g., adjusting the energy demand and supply by controlling the electricity rates according to the energy demand) and incentive-based DR (e.g., providing incentives when saving electricity during peak load period) [158]. By applying the concept of DR strategies in the building's usage stage, this study proposed a way of saving energy by providing real-time techno-economic information of energy (i.e., energy demand and prices at the present time) to the building occupants as a dynamic strategy for implementing nZEB.

There have been various studies that analyzed energy-saving through behavioral change caused by providing the energy-related information to end users of a building [159–168]. Anderson et al. (2017) conducted a study to analyze the behavior change over two years caused by sending a message regarding the energy consumption for students living in a dormitory complex on a university campus in Seoul, South Korea [162]. Kemp-Hesterman and Glick (2014) investigated the effects of human behavior on the electricity consumption, and the optimal solution to reducing the electricity consumption by inducing human behavior change using mixed methods (e.g., interviews) [164]. Endrejat et al. (2015) provided the factors (e.g., motivational interviewing) to consider when trying to induce human-behavior-based energy-saving in a non-residential building from a psychological viewpoint [168]. The studies mentioned above are significant in that they analyzed building energy-saving through human behavior change, but they had restrictions as their analyses were conducted based on energy data over weekly, monthly, or annual units rather than on real-time data. In other words, the immediate behavior change was not reflected in energy savings because the previous studies did not consider real-time energy-related information. Therefore, analyzing the immediate energy-saving by providing real-time energy data to the building occupants in the building usage phase remains a challenge.

4. Conclusions

This study carried out a state-of-the-art review on the recent studies regarding the implementation strategies of nZEB. As a result, previous studies related to nZEB can be classified into two categories based on the following perspectives: (i) passive strategies; and (ii) active strategies.

(1) Passive strategies: The passive strategies refer to reducing the building energy demands at the early stage of a building's life cycle through an architectural design technique. In this study, passive strategies were classified as passive sustainable design and EST. Most studies related to the passive strategies (i.e., passive sustainable design and EST) were analyzed for building energy performance according to design variables via energy simulation tools. Analysis of these studies showed that applying passive strategies to buildings is effective in terms of energy savings, but it is not sufficient in terms of implementing nZEB.
(2) Active strategies: The active strategies mainly represent ways to reduce building energy consumption through energy production. This study conducted an extensive literature review on these active strategies focusing on the RE and back-up system for RE. The studies regarding active strategies (i.e., RE and back-up system for RE) mostly analyzed building energy performance through experiments with energy simulation tools. The analysis of the previous studies showed that RE is still not enough to realize nZEB, and in case of the back-up system, especially ESS, the technical and economic effects may be lower because they complement the RE based on historical data.

Based on the extensive literature review, this study proposed advanced strategies for nZEB implementation in accordance with a building's life cycle (i.e., the early phase and usage phase of a building's life cycle) as follows: (i) integration and optimization of the passive and active strategies in the early phase of a building's life cycle; and (ii) real-time monitoring of the energy performance during the usage phase of a building's life cycle.

(1) Integration and optimization of the passive and active strategies in the early phase of a building's life cycle: This study proposed integration and optimization of the passive and active strategies as the advanced strategies for implementing nZEB in order to overcome the limitations of previous studies by the following two perspectives: (i) there are very few studies evaluating buildings technical and economic performance by applying both passive and active strategies; (ii) the technical effects (e.g., energy savings) that occur through sequential application of passive and active strategies are far superior.
(2) Real-time monitoring of the energy performance during the usage phase of a building's life cycle: This study presented the following two aspects of real-time monitoring of the energy performance as advanced strategies so as to realize nZEB by considering the limitations of existing studies and diversification of buildings: (i) developing an integrated real-time monitoring system for buildings' energy performance; and (ii) analyzing the energy-saving potential through the end-user behaviors.

It is expected that this study can be used as a guideline for policymakers, energy researchers, and practitioners in order to understand the current level and to establish future directions from the perspectives of nZEB.

Acknowledgments: This work was supported by a grant (17CTAP-C114950-02) from Technology Advancement Research Program (TARP) funded by Ministry of Land, Infrastructure and Transport of Korean government.

Author Contributions: All authors (Jeongyoon Oh, Taehoon Hong, Hakpyeong Kim, Jongbaek An, Kwangbok Jeong, and Choongwan Koo) wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

a-Si	Amorphous silicon
BIPB	Building-integrated photovoltaic blind system
BIPV	Building-integrated photovoltaic system
CFD	Computational fluid dynamics
CMr	Construction manager
DR	Demand response
ESS	Energy storage system
EST	Energy-saving techniques
GHG	Greenhouse gas
i-MOO model	Integrated multi-objective optimization model
LED	Lighting emitting diode
NPV	Net present value
nZEB	Net-zero energy building
PCM	Phase change material
PP	Payback period
PV	Photovoltaic
RE	Renewable energy
SIR	Saving-to-investment ratio
WWR	Window-to-wall ratio

Appendix A

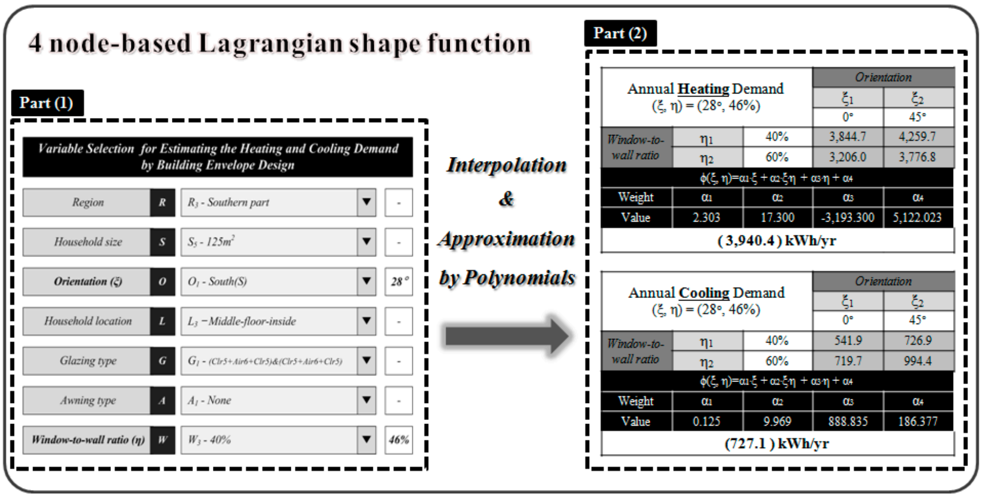

Figure A1. Four-node-based Lagrangian finite element model for estimating heating and cooling demand.

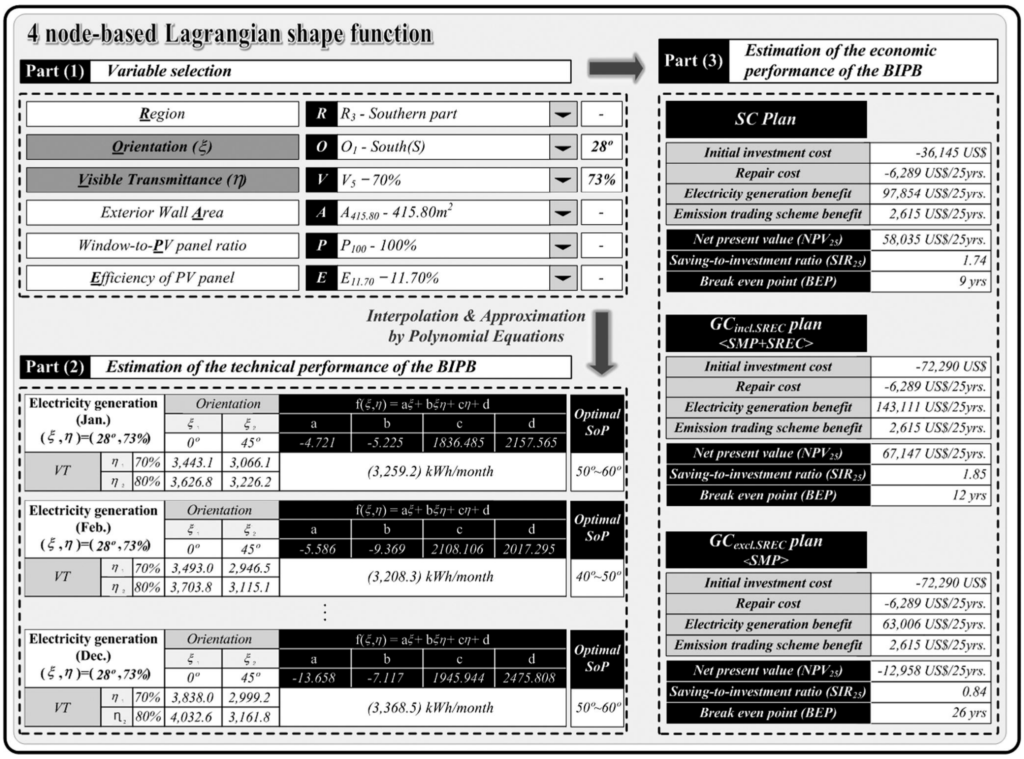

Figure A2. Four-node-based Lagrangian finite element model for estimating the amount of electricity generated from building-integrated PV blind system.

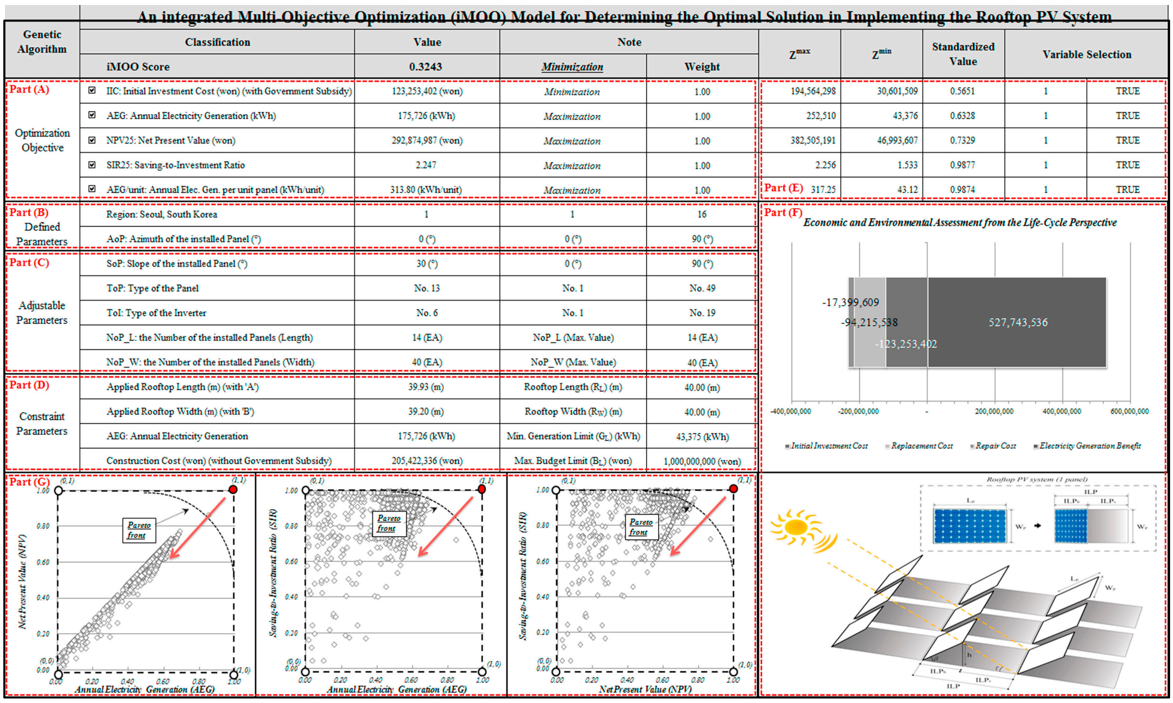

Figure A3. Graphical user interface of the integrated multi-objective optimization (iMOO) for determining the optimal solution in implementing the rooftop PV system.

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