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Article

# Selection of Energy Improvement Factors and Economic Analysis of Standard MDU Complexes in Korean Metropolitan Regions

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**Abstract:** In Korea, energy consumption within apartments in metropolitan areas accounted for more than 33% of the total energy consumption by buildings in 2020. In this study, in order to increase the energy efficiency of MDU (multi-dwelling unit) complexes in metropolitan areas, improvement factors and economic effects were analyzed using ECO2, a building energy efficiency evaluation program. Optimal improvement measures are proposed, to reduce the economic burden on users by applying energy saving technologies. This study was conducted in four stages; in the first stage, using ECO2 software, five types of apartments were selected as standards among 46 complexes. Standard MDUs were selected if more than two factors were satisfied from among the following: (1) household type, (2) average exterior wall insulation and window performance, (3) average energy consumption and demand per unit area per year, (4) average applied facility system, and (5) average monthly energy demand per unit area. In the second stage, improvement factors were derived by analyzing the 10 most recent energy efficient MDU complexes. The third stage involved analysis of the energy saving effect generated by the improvement of windows and total heat exchangers in five selected complexes. Primary energy consumption per unit area per year improved from 158.8 to 132. kWh/m$^2$y in complex E, which had been upgraded from 'floor heating system' to 'total heat exchanger'. Finally, in the fourth stage, optimal improvement factors were selected for economic analysis. By simultaneously applying the optimal improvement factors, such as windows and total heat exchanger, to the M complex, primary energy consumption per unit area per year was improved from 147.6 to 111.4 kWh/m$^2$ y. When optimal improvement factors were applied to 59 m$^2$, 74 m$^2$, 84 m$^2$ types in complex M, life cycle cost savings of energy consumption for 30 years became $1384~1970.

**Keywords:** MDU (multi-dwelling unit; apartment); building energy assessment program ECO2; energy demand; energy consumption; primary energy; energy efficiency; lifecycle cost (LCC)



**Citation:** Lee, K.-W.; Kim, Y.I. Selection of Energy Improvement Factors and Economic Analysis of Standard MDU Complexes in Korean Metropolitan Regions. *Energies* **2022**, *15*, 4042. https://doi.org/10.3390/en15114042

Academic Editors: Sławomir Rabczak, Daniel Słyś and Krzysztof Nowak

Received: 25 April 2022
Accepted: 28 May 2022
Published: 31 May 2022



## 1. Introduction

Given the global shortage of fossil fuel reserves and the emergence of climate change, increased attention is being devoted to greenhouse gas reduction and energy conservation [1,2]. In October 2021, the Republic of Korea deliberated and decided on the '2050 Carbon Neutral Scenario Plan' and the '2030 Nationally Determined Contribution (NDC) Upgrade Plan' [3,4]. As shown in Figure 1a, upgraded plans increased by 40% the total greenhouse gas emission reduction goal, compared with the previously established 2018 target [3,5]. In particular, the reduction target in the building sector was strengthened by 32.8% compared with the 2018 reduction rate, with the goal of reducing 35.0 million tons of $CO_2$eq [3].

In order to achieve the $CO_2$ emission reduction target in the building sector, energy and eco-friendly buildings are being evaluated worldwide [6,7]. Each country has developed and utilized standard indicators and systems for evaluation of building energy efficiency [8,9].

To achieve the NDC upgrade plan within the building sector, various domestic incentives have been launched, including strengthening the energy efficiency ratings of new buildings, zero-energy building certification, energy diagnosis of existing buildings, and green remodeling businesses, and their standards are being upgraded [5,10–12].

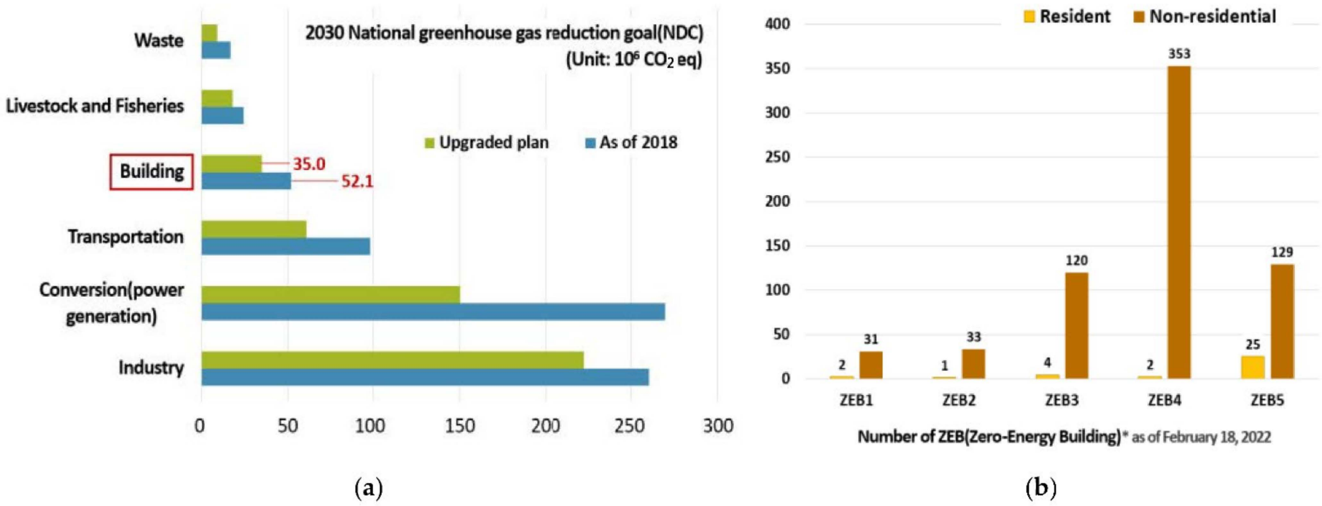
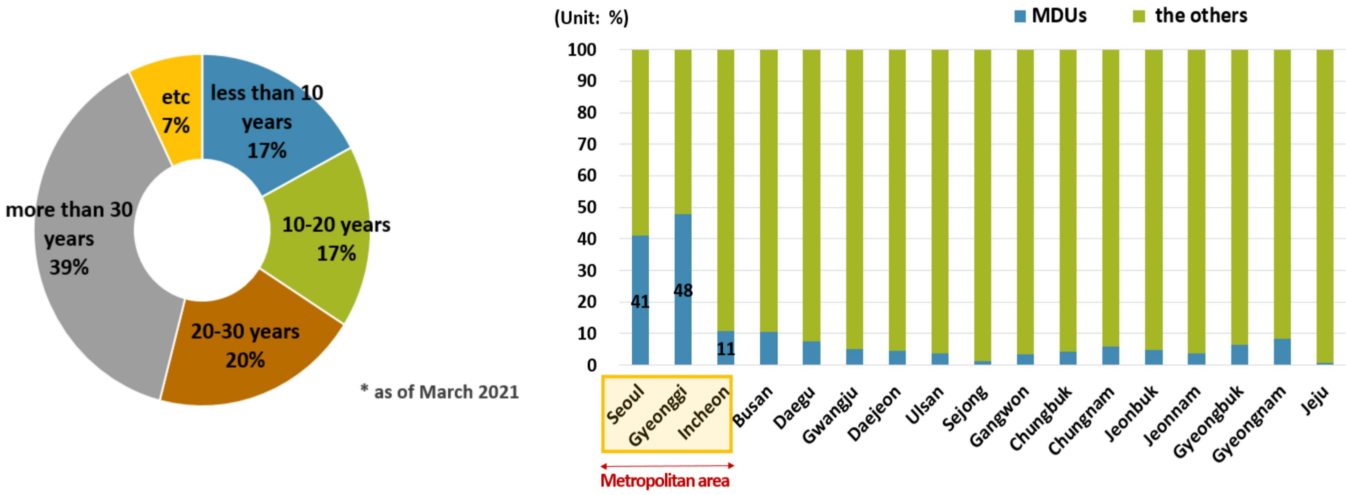



**Figure 1.** (**a**) 2030 national greenhouse gas reduction goals (NDC) [3]; (**b**) Number of buildings certified as preliminary zero-energy buildings (ZEBs) [13].

Considering zero-energy buildings certified in recent years, there have been significantly fewer certification cases for residential buildings compared to nonresidential buildings, as shown in Figure 1b [13].

Currently, zero-energy building certification is mandatory for new buildings, but it is difficult to apply this rule to existing buildings [13,14]. In addition, based on an examination of building status in the domestic 'building life history management system' (Figure 2a), approximately 59% of buildings are older than 20 years [5,15,16]. With regard to the green remodeling project, which is being carried out in Korea to improve the energy ratings of existing buildings, support projects are actively being conducted, but it is difficult to evoke positive perceptions owing to the economic burden [17–20]. In particular, in terms of the energy consumption of buildings, it was observed that MDUs (multi-dwelling units) accounted for the highest proportion [20,21]. As shown in Figure 2b, based on energy consumption by building use in 2020 described in the 'Green Together-Building Energy Statistics', the average building energy consumption for MDUs in metropolitan areas is 33% or more [22]. It was also noted that MDUs accounted for 48% of the total energy consumed in Gyeonggi-do province [23].

As mentioned previously, policies and R&D for energy saving in buildings are expanding worldwide due to climate change and a decrease in fossil fuel reserves. In particular, various domestic incentives are being actively carried out to improve the energy use of buildings in Korea. However, the energy consumption of MDUs in the metropolitan area accounted for more than 33% of the total energy consumption by buildings in 2020. Therefore, research is needed to lower the energy consumption of MDUs in the metropolitan area. As shown in Table 1, this study presents suggestions for the improvement factors for MDU complexes with high energy consumption in metropolitan areas. To present reasonable results, standard materials and equipment elements that are currently applied to MDUs were studied. Futhermore, analysis of the improvement effects and proposals for optimal improvement factors to reduce the economic burden on users were also studied. Reduction of primary energy consumption per unit area per year, and life cycle cost savings, were compared when optimal improvement factors were applied to selected complexes.




(**a**) (**b**)

**Figure 2.** (**a**) Age status of domestic buildings as of March 2021 [15,16]; (**b**) Comparison of energy consumption by region for MDUs and other uses [22].

**Table 1.** Comparison of literature review.

| Reference | Contents |
|---|---|
| [1,2]<br>[3]<br>[4]<br>Major topic | Shortage of fossil fuel reserves and emergence of climate changes.<br>2050 Carbon Neutral Scenario Plan.<br>2030 Nationally Determined Contribution (NDC) Upgrade Plan.<br>Energy technology to reduce $CO_2$eq in buildings. |
| [5,12]<br>[15,16]<br>Major topic | Reinforcement of energy efficiency ratings focused on new buildings and zero-energy building certification.<br>Approximately 59% of buildings are older than 20 years.<br>Research into energy saving in existing buildings. |
| [20,21]<br>[22,23]<br>Major topic | The energy consumption of MDUs accounts for the highest proportion [20,21].<br>High proportion of energy consumption in the metropolitan area [22,23].<br>Improvement of energy consumption in apartment complexes in the metropolitan area. |
| This work | Selection of energy improvement factors and economic analysis of standard MDU complexes in Korea metropolitan region. |

## 2. Methods

This study was conducted on 46 MDUs that obtained building energy efficiency ratings and received permits between 2014 and 2015. To suggest elements for improvement in metropolitan areas, economic analysis was carried out for these MDUs [23]. In addition, 10 MDUs that obtained certifications and received building permits in 2021 were analyzed to select improvement factors with regard to applied materials and facilities [23]. As shown in the research methodology presented in Figure 3, the research process was divided into four stages; standard MDU selection using ECO2, standard MDU improvement factor selection, improvement factor application effect analysis and optimal improvement factor selection, and economic analysis of the optimal plan.

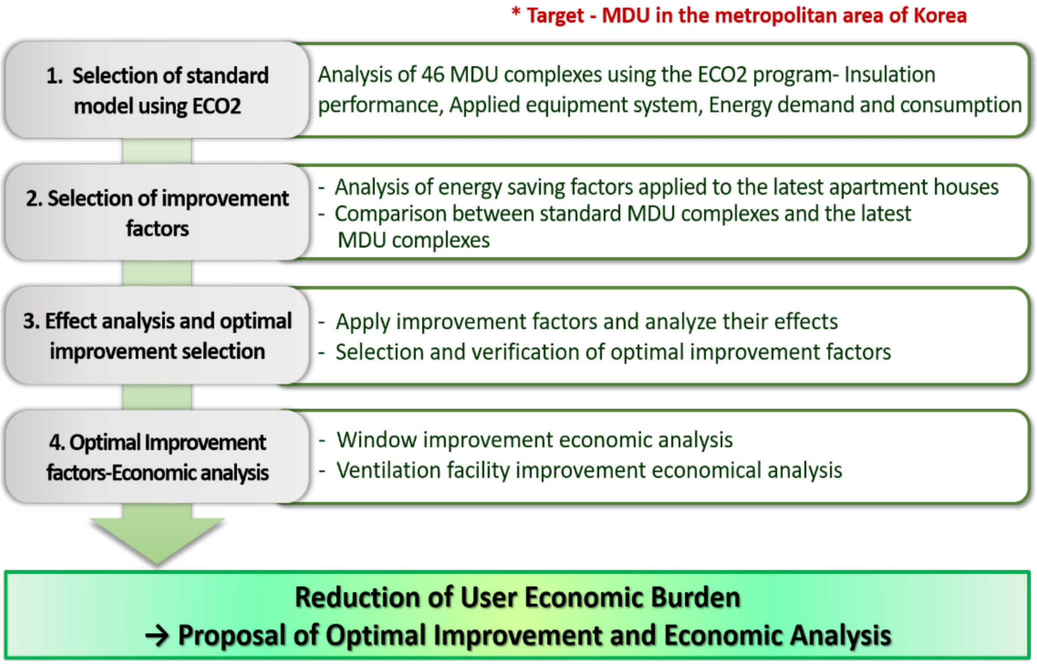



**Figure 3.** Research methodology: selection of optimal improvement factors and economic analysis of MDUs in metropolitan areas of Korea, using the building energy assessment program ECO2.

## 3. Selection of Standard MDU Using ECO2

### *3.1. Definition of ECO2*

From 1 September 2013, domestic building energy efficiency rating certifications have been issued to residential and nonresidential buildings that have been evaluated by the building energy evaluation program ECO2. [24,25]. The ECO2 program utilizes weather data of 13 regions in Korea in accordance with the 'Rules for Building Energy Efficiency Rating Certification and Zero Energy Building Certification'. Energy consumption simulations are carried out for heating, cooling, hot water supply, lighting, ventilation, and new renewable systems. As a result, energy demand per unit area per year, energy consumption, and primary energy consumption are calculated [24–27]. ECO2 is a building energy consumption evaluation program based on the ISO 13790 and DIN 18599 [25–28]. The ECO2 program is mainly used for building energy evaluation, including zero energy building evaluation [29,30]. It is a program similar to Energy Plus, a dynamic analysis program that is widely used for building energy evaluation [31–33]. The ECO2 program was applied to MDUs between 2014 and 2015 [24,25].

### *3.2. Standard MDU*

For selection of standard MDUs, the floor area, exterior wall insulation, window types, ventilation facilities, new and renewable energy facilities, energy demand, energy consumption, and primary energy consumption were analyzed for 46 MDU complexes that obtained building energy efficiency ratings in 2014 and 2015.

#### 3.2.1. Floor Area

The floor areas of 46 complexes were analyzed, to study how area affects facility capacity, wall insulation, and window size. A total of 73 area types were applied to 46 complexes, with the smallest type being 11 m$^2$ and largest type 273 m$^2$. Figure 4 shows the results of the most frequently applied types across 46 complexes consisting of 46,398 households in total. After analyzing 46 complexes, the most applied types were 59 m$^2$, 74 m$^2$, and 84 m$^2$. Among 46 complexes, 19 of them had 59 m$^2$, 74 m$^2$, and 84 m$^2$ types.

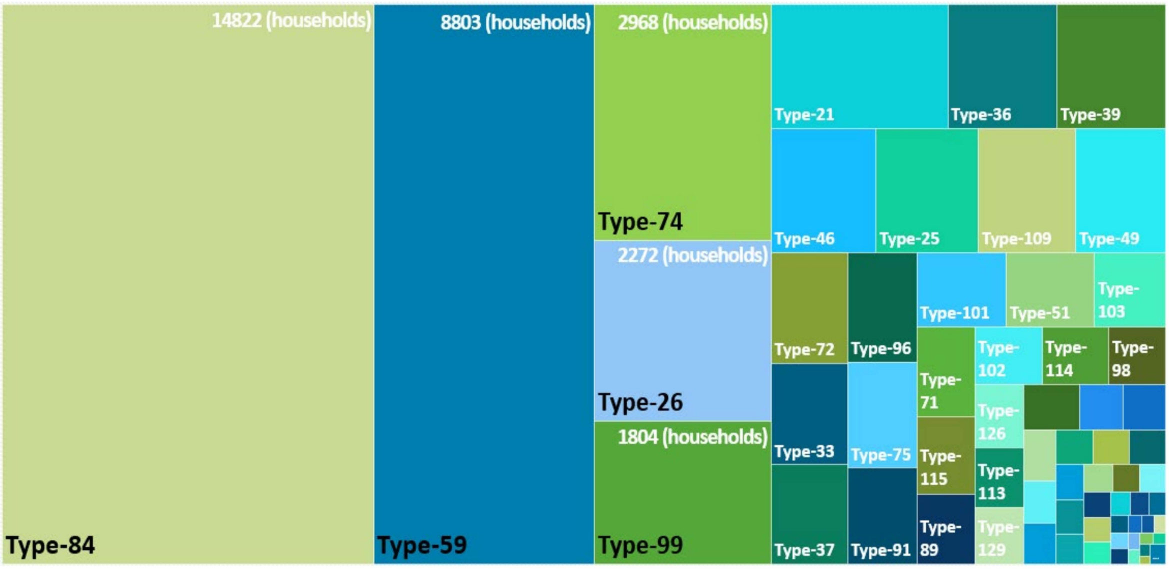



**Figure 4.** Type distribution of 46,398 households in 46 complexes.

### 3.2.2. Insulation Performance and Facility Status

First, exterior wall insulation performance was studied to reveal how heating energy demand, heating energy consumption and primary energy consumption were affected [34]. Insulation materials and thermal conductivity applied to the exterior walls were investigated, as shown in Table 2. The most frequently applied exterior wall insulation in the 46 complexes was 'bead method thermal insulation plate type 2 No. 2'.

**Table 2.** Results of investigation on external wall insulation in 46 MDU complexes.

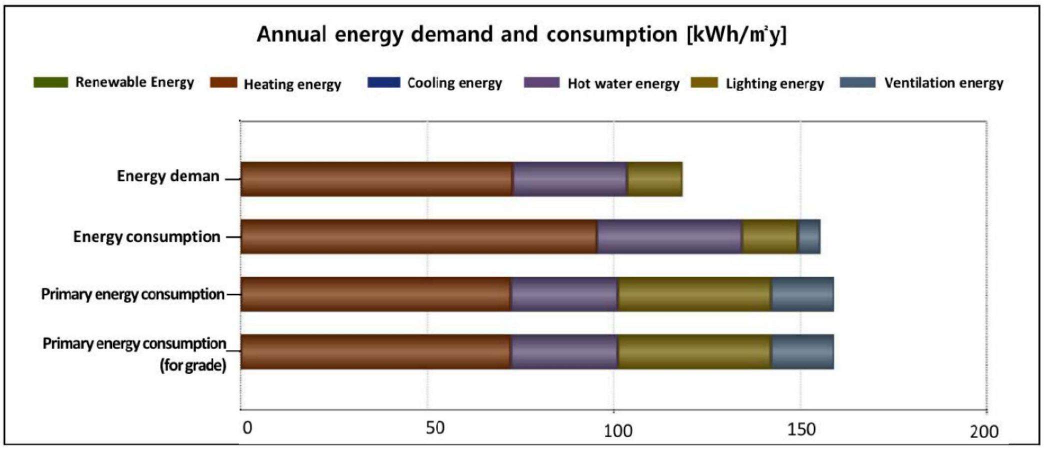
| Insulation Material | Thermal Conductivity ($W/m^2K$) | Number of Applied Complexes |
|---|---|---|
| Hard urethane type 1 No. 3 | 0.025 | 3 |
| Hard urethane type 2. No. 2. | 0.023 | 8 |
| Glass wool thermal insulation plate 24K | 0.037 | 2 |
| Bead method thermal insulation plate type 1 No. 2 | 0.035 | 1 |
| Bead method thermal insulation plate type 2 No. 1 | 0.031 | 2 |
| Bead method thermal insulation plate type 2 No. 2 | 0.032 | 21 |
| Bead method thermal insulation plate type 2 No. 3 | 0.033 | 5 |
| Bead method thermal insulation plate type 2 No. 4 | 0.034 | 2 |
| Extrusion method thermal insulation plate No. 1 | 0.024 | 1 |
| Extrusion method thermal insulation plate special | 0.027 | 1 |

Then, as a result of examining window insulation performance [35,36], which affects insulation performance, heating energy demand, energy consumption and primary energy consumption of buildings, it was found that 'air-injected low-e double-glazed windows (soft coating)' were applied in 12 complexes. For balcony-extended windows, 'argon-injected low-e double glazed (soft coating) + air-injected low-e double glazed (soft coating)' were applied in 18 complexes.

Third, when analyzing heating systems, cooling systems, ventilation, and new and renewable systems for the facility application status analysis, cooling systems were excluded because these are the occupants' responsibility. Among 46 MDU complexes surveyed, no complex had adopted the new and renewable system. As a result of the analysis of heating system status, it was found that 37 complexes used district heating. In ventilation system status analysis, 27 complexes used total heat exchangers which have the feature of ventilation energy recovery when exchanging indoor and outdoor air.

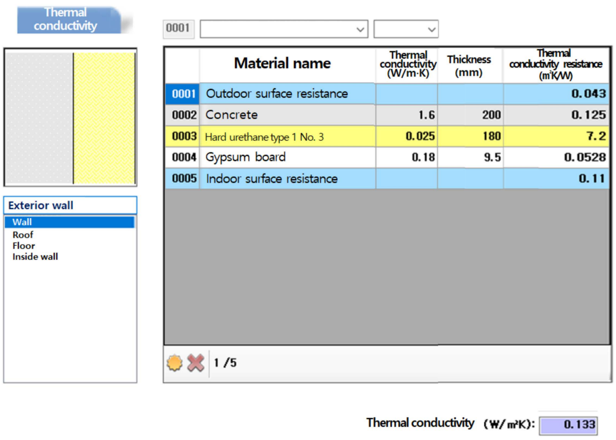
### 3.2.3. Annual Energy Demand, Energy Consumption and Primary Energy Consumption

Following ECO2 program analysis, results were obtained for annual energy demand, energy consumption, primary energy consumption, and $CO_2$ generation, per unit area per year. Here, 'energy demand' means energy per unit area per year required for heating, cooling, hot water supply and lighting of a building; 'energy consumption' means energy per unit area per year consumed for heating, cooling, hot water supply, lighting, and ventilation [24,37]; 'primary energy consumption' is the standard for evaluating the building energy efficiency rating certification, referring to energy per unit area per year including energy conversion efficiency and losses in the fuel supply process [24,38,39]. Figure 5 shows the building energy efficiency rating certification grade, energy demand per unit area per year, energy consumption per unit area per year, and primary energy consumption per unit area per year for the 46 MDU complexes analyzed using the ECO2 program.



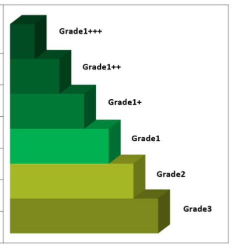

| | Renewable Energy | Heating energy | Cooling energy | Hot water energy | Lighting energy | Ventilation energy | Sum |
|---|---|---|---|---|---|---|---|
| Energy demand | 0.0 | 72.8 | 0.0 | 30.7 | 14.9 | 0.0 | 118.3 |
| Energy consumption | 0.0 | 95.3 | 0.0 | 38.9 | 14.9 | 6.2 | 155.3 |
| Primary energy consumption | 0.0 | 72.3 | 0.0 | 28.7 | 41.0 | 16.9 | 159.0 |
| $CO_2$ emission | 0.0 | 16.1 | 0.0 | 6.4 | 7.0 | 2.9 | 32.4 |
| Primary energy consumption (for grade) | 0.0 | 72.3 | 0.0 | 28.7 | 41.0 | 16.9 | 159.0 |

(**a**)




(**b**)

| Grade | Primary energy consumption per unit area per year(kWh/m²y) |
|---|---|
| 1+++ | Less than 60 |
| 1++ | More than 60 and Less than 90 |
| 1+ | More than 90 and Less than 120 |
| 1 | More than 120 and Less than 150. |
| 2 | More than 150 and Less than 190. |
| 3 | More than 190 and Less than 230. |




(**c**)

**Figure 5.** Input and output of ECO2 program; (**a**) Analysis results: annual energy demand, energy consumption, and primary energy consumption (**b**) Input of external wall insulation (**c**) primary energy consumption per unit area per year by building energy efficiency grade.

According to the analysis of 46 MDUs, the average energy demand per unit area per year was 107.5 kWh/m$^2$y, and the average energy consumption per unit area per year was 146.5 kWh/m$^2$y. In addition, the average primary energy consumption per unit area per year was 150.7 kWh/m$^2$y.

This corresponded to Grade 2 of the building energy efficiency grading system. Figure 5c shows the primary energy consumption per unit area per year for each energy efficiency grade.

#### 3.2.4. Selection of Standard MDU Complex

Among the 46 MDU complexes, 19 complexes including 59 m$^2$, 74 m$^2$, and 84 m$^2$ types were selected as standard groups due to their frequency of occurrence. Figure 6 shows five factors for selecting standard MDUs. Floor area, exterior wall and window insulation, energy demand and energy consumption, facility system, and monthly energy demand were analyzed. Among 19 MDUs, five complexes E, F, J, M, and P satisfied two or more of the five factors, and were selected as standard MDU complexes for this study.

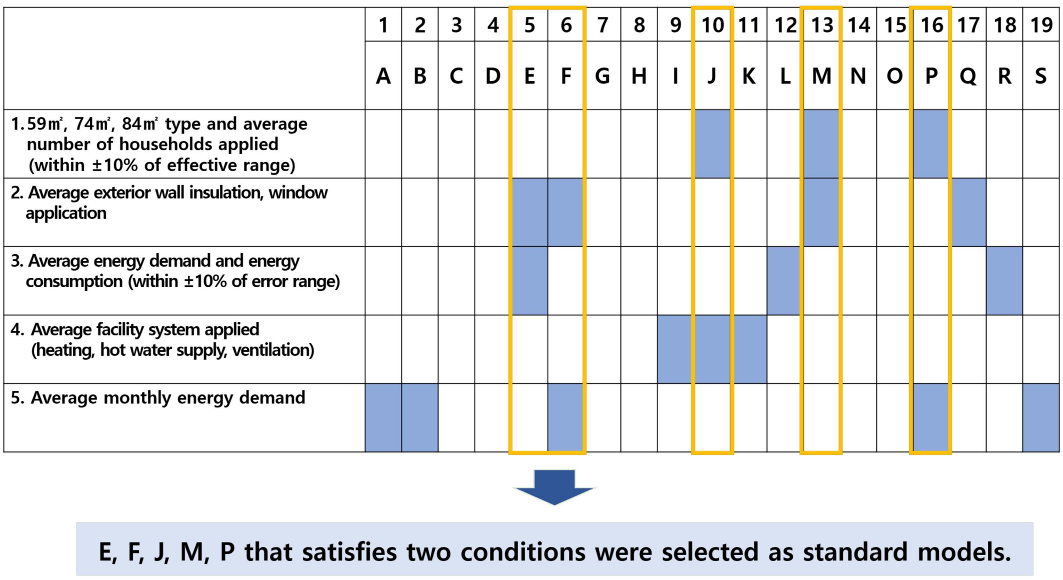



**Figure 6.** The frequency analysis results showing occurrence of two or more of the five types of 1. TYPE, 2. exterior wall insulation, 3. windows, 4. ventilation, 5. energy demand and consumption, out of 46 MDU complexes.

## 4. Selection of Improvement Factors

In order to improve the energy efficiency of E, F, J, M, and P complexes, selected as standard MDUs, we analyzed the technology applied to the 10 latest MDUs that obtained building energy efficiency Grade 1+ or higher in 2021. Through this analysis, improvement factors were selected.

### *4.1. Energy-Saving Factors Applied to the Latest MDU Complexes*

#### 4.1.1. Insulation Performance and Facility System Status

Exterior wall insulation, window insulation, heating system, ventilation system, and new and renewable system application status were analyzed for 10 MDU complexes that obtained building energy efficiency grades of 1+ or higher. First, according to the analysis of exterior wall insulation, 'hard urethane foam type 1 No. 3′ was applied to 9 complexes. 'Hard urethane foam type 1 No. 3′ has a thermal conductivity of 0.025 W/m·K. This thermal conductivity is less by 0.007 W/m·K than the 0.032 W/m·K of the 'bead method warming plate type 2 No. 2′, which was the most frequently applied insulation across the 46 complexes [40–43]. Energy saving effects can be expected after improvement of exterior wall insulation. Second, in the case of windows, 'argon injection-(low-e double-glazed glass + general double-glazed glass)' was applied in five complexes. For balcony extension windows, 'argon injection-(low-e double glazing + double glazing (soft coating))' was applied in seven complexes. Third, heating systems, ventilation systems, and renewable systems were analyzed. District heating systems were applied in eight complexes. Total heat exchangers with energy recovery were applied in all 10 complexes. In terms of new and renewable systems, PV(photo voltaic) was applied in nine complexes.

#### 4.1.2. Energy Demand, Energy Consumption and Primary Energy Consumption Analysis

The 10 selected MDU complexes that acquired certification in 2021 were analyzed using the ECO2 program. As a result, the average energy demand per unit area per year was found to be 74.5 kWh/m$^2$y. The average energy consumption per unit area per year was 111.1 kWh/m$^2$y. The average primary energy consumption per unit area per year was 102.9 kWh/m$^2$y, which corresponded to building energy efficiency Grade 1+. Comparison of the average monthly heating energy demand per unit area of 10 MDUs certified in 2021 and 46 MDUs certified in 2014–2015 was analyzed, as shown in Table 3. Monthly average heating energy demand per unit area of MDU certified in 2021 was reduced by 1.7 kWh/m$^2$ when compared to complexes certified during 2014 and 2015.

**Table 3.** Comparison of monthly heating energy demand per unit area.

| | Heating Energy Demand per Unit Area (kWh/m$^2$) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Avg.** |
| 2014~2015 | 17.5 | 13.0 | 7.9 | 1.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 7.2 | 14.0 | 5.2 |
| 2021 | 12.9 | 8.3 | 5.5 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 4.2 | 9.5 | 3.5 |
| Savings | 4.6 | 4.7 | 2.4 | 1.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 2.9 | 4.5 | 1.7 |

### *4.2. Analysis of Improvement Effect*

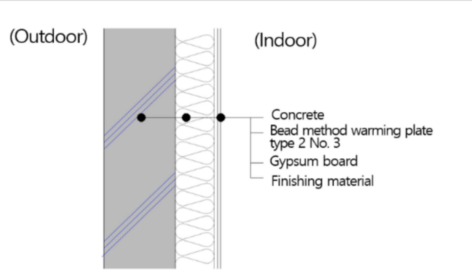
Energy saving products including exterior wall insulation, windows, mechanical facility systems, and renewable systems applied to 10 MDUs certified in 2021 as Grade 1+ or higher were analyzed. These products were applied to standard models E, F, J, M and P to study their effects and also for selecting optimal improvement factors. In addition, to verify the effect of the improvement factors, the results of ECO2 simulation were compared with the actual measurements.

#### 4.2.1. Effect of Exterior Wall Insulation Improvement

As a result of implementing exterior insulation material 'hard urethane type 1 No. 3′ in E, F, J, M, and P MDU complexes, the P complex saw the most significant effect in reducing energy demand and energy consumption, as shown in Figure 7a. In the case of the P complex, with 'bead method warming plate type 2 No. 3′, insulation applied in the past, the overall heat transfer coefficient of the exterior wall was 0.251 W/m$^2$K, calculated as shown in Figure 7b. The overall heat transfer coefficient became 0.194 W/m$^2$K, an improvement of 0.057 W/m$^2$K. As a result of implementing higher exterior wall insulation in the P complex, the annual primary energy consumption reduction per unit area became 3.2 kWh/m$^2$y.

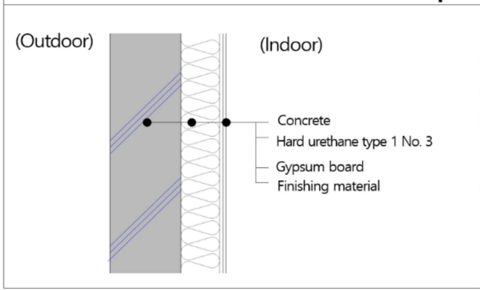
Table 4 shows that the average annual primary energy consumption reduction per unit area for E, F, M, and P was 1.9 kWh/m$^2$y. J complex was excluded since in this complex, 'hard urethane type 2 No. 2′ which has higher performance than 'hard urethane type 1 No. 3′ was already applied and thus required no further improvement.

**Wall composition before improvement**




| | Material name | Thickness (mm) | Overall heat transfer coefficient (W/m·K) | Thermal resistance (m²K/W) |
|---|---|---|---|---|
| 1 | Outdoor surface resistance | - | - | 0.043 |
| 2 | Concrete | 220 | 1.6 | 0.138 |
| 3 | Bead method warming plate type 2 No. 3 | 120 | 0.033 | 3.636 |
| 4 | Gypsum board | 9.5 | 0.18 | 0.053 |
| 5 | Finishing material | - | - | - |
| 6 | Indoor surface resistance | - | - | 0.110 |
| | Thermal conductivity (W/m²K) | | | 0.251 |

**Wall composition after improvement**




| | Material name | Thickness (mm) | Overall heat transfer coefficient (W/m·K) | Thermal resistance (m²K/W) |
|---|---|---|---|---|
| 1 | Outdoor surface resistance | - | - | 0.043 |
| 2 | Concrete | 220 | 1.6 | 0.138 |
| 3 | Hard urethane type 1 No. 3 | 120 | 0.025 | 4.800 |
| 4 | Gypsum board | 9.5 | 0.18 | 0.053 |
| 5 | Finishing material | - | - | - |
| 6 | Indoor surface resistance | - | - | 0.110 |
| | Thermal conductivity (W/m²K) | | | 0.194 |

(**a**)


(**b**)

**Figure 7.** ECO2 input for P complex. (**a**) Composition of exterior wall; (**b**) Exterior wall insulation.

**Table 4.** Changes in energy demand and energy consumption of E, F, J, M, and P MDU complexes before and after exterior wall improvement.

| Improvement Status | MDU | Energy Demand per Unit Area per Year (kWh/m$^2$ y) | Energy Consumption per Unit Area per Year (kWh/m$^2$ y) | Primary Energy Consumption per Unit Area per Year (kWh/m$^2$ y) |
|---|---|---|---|---|
| Before | E | 118.2 | 155.2 | 158.8 |
| | F | 102.6 | 158.3 | 168.3 |
| | M | 119.3 | 150.8 | 147.6 |
| | P | 96.5 | 145.5 | 143.3 |
| | Average | 109.15 | 152.45 | 154.5 |
| After | E | 116.5 | 153.2 | 157.3 |
| | F | 100.5 | 155.4 | 166.2 |
| | M | 118.4 | 149.7 | 146.8 |
| | P | 93.2 | 141.1 | 140.1 |
| | Average | 107.2 | 149.9 | 152.6 |

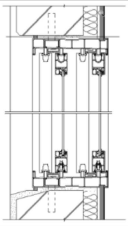
### 4.2.2. Effect of Window Improvement

For recently built energy-saving MDUs, 'argon injection low-e double-glazed windows (soft coating)' with thermal conductance of 0.717 W/m$^2$K were applied. To analyze the window improvement effect, inputs for the ECO2 program were carried out by dividing the window category into household windows and balcony extension windows. Figure 8a shows the ECO2 input conditions for balcony extension windows in the M complex, which showed the best result. In the case of the balcony extension type windows in the M complex, 'argon injection low-e double-glazed (soft coating) + air-injected low-e double-glazed (soft coating)' of 1.3 W/m$^2$K was applied. As shown in Figure 8b, by applying air to one side of the filler, the thermal conductance of the improved window was reduced by 0.58 W/m$^2$K compared to the old type [44–46]. As a result of the ECO2 analysis of E, F, J, M, and P complexes, the average annual primary energy consumption reduction per unit area per year after improvement was found to be 8.5 kWh/m$^2$y, as shown in Table 5.

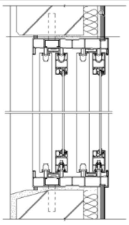
**Table 5.** Changes in energy demand and energy consumption of E, F, J, M, and P MDUs before and after window improvement.

| Improvement Status | MDU | Energy Demand per Unit Area per Year (kWh/m$^2$ y) | Energy Consumption per Unit Area per Year (kWh/m$^2$ y) | Primary Energy Consumption per Unit Area per Year (kWh/m$^2$ y) |
|---|---|---|---|---|
| Before | E | 118.2 | 155.2 | 158.8 |
| | F | 102.6 | 158.3 | 168.3 |
| | J | 92.7 | 121.9 | 137.5 |
| | M | 119.3 | 150.8 | 147.6 |
| | P | 96.5 | 145.5 | 143.3 |
| | Average | 105.9 | 146.3 | 151.1 |
| After | E | 109.7 | 145.1 | 151.3 |
| | F | 96.2 | 149.6 | 161.9 |
| | J | 84.9 | 112.3 | 130.3 |
| | M | 104.2 | 132.9 | 134.4 |
| | P | 87.8 | 134.1 | 134.9 |
| | Average | 96.6 | 134.8 | 142.6 |

**Window composition before improvement**

| | | Material name | Thickness (mm) |
|---|---|---|---|
| (Outdoor)  (Indoor) | 1 | **Inside** - window configuration<br>Low-e double-layer glass (soft coating, argon injection) | (5+12+5) |
| | 2 | **Outside** - window configuration<br>Low-e double-layer glass (soft coating, air) | (5+12+5) |
| | 3 | Window frame - Plastic | |
| | | **Thermal conductance (W/㎡K)** | 1.300 |

**Window composition after improvement**

| | | Material name | Thickness (mm) |
|---|---|---|---|
| (Outdoor)  (Indoor) | 1 | **Inside** - window configuration<br>Low-e double-layer glass (soft coating, argon injection) | (5+12+5) |
| | 2 | **Outside** - window configuration<br>Low-e double-layer glass (soft coating, argon injection) | (5+12+5) |
| | 3 | Window frame - Plastic | |
| | | **Thermal conductance (W/㎡K)** | 0.717 |

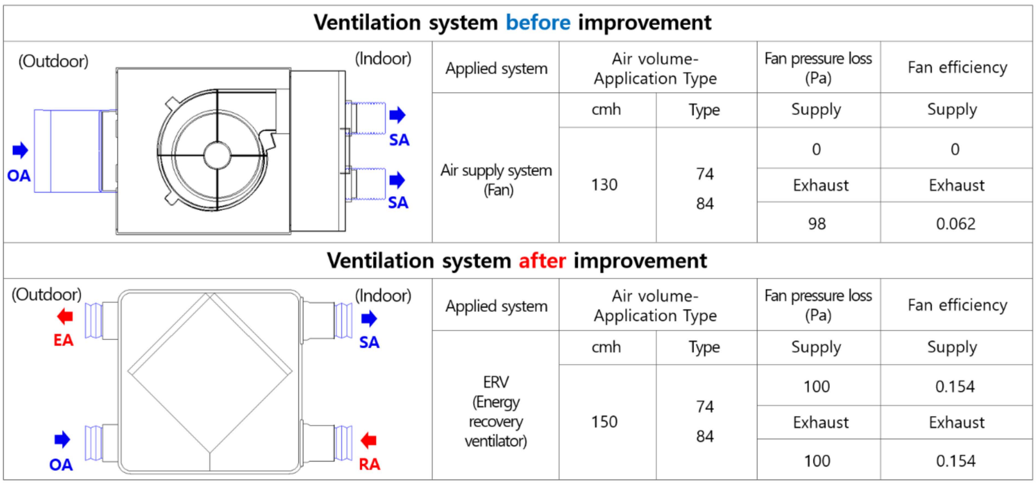
(**a**)


(**b**)

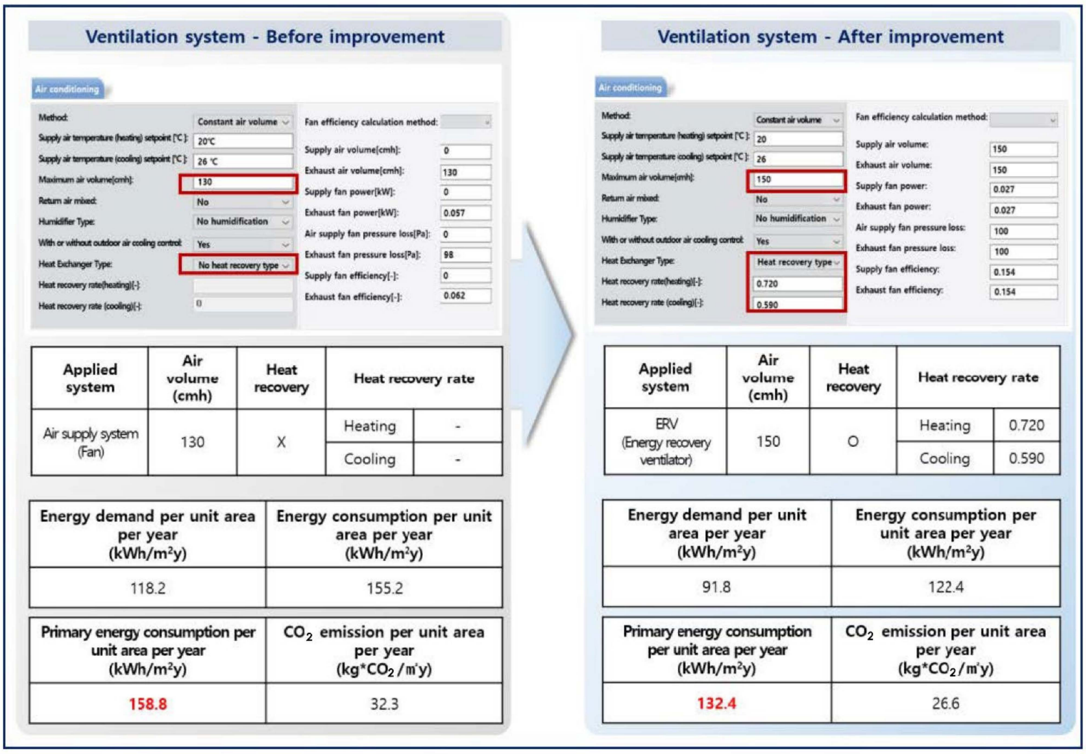
**Figure 8.** (**a**) Window composition before and after improvement in M MDU; (**b**) Window input and simulation calculation results before and after ECO2 simulation window improvement in M MDU.

### 4.2.3. Effect of Ventilation System

For the ventilation systems in new energy-saving MDUs, 100 cmh (cubic meter per hour, $m^3/h$) was applied to the 59 $m^2$ type, and 150 cmh was applied to the 74 $m^2$ and 84 $m^2$ types. Heat recovery efficiencies applied to the 59 $m^2$ type were heating 77% and cooling 60%, whereas those applied to the 74 m$^2$ and 84 m$^2$ types were heating 72% and cooling 59%. Figure 9a lists input values for the ECO2 program for analyzing the ventilation system improvement effect. Input factors were heat recovery rate (efficiency), air volume flow rate, fan power, and fan pressure loss [24]. Figure 9b shows the input conditions of the E complex which showed the best improvement result. In complex E, the 'floor heat supply system' was applied before the improvement. This is a system that supplies outdoor air to the inside of the house using floor heat [47]. If the floor heat supply system was replaced by total heat exchanger (ERV) used in new energy-saving MDUs, the primary energy consumption per unit area per year was reduced by 26.4 kWh/m$^2$y.




(**a**)




(**b**)

**Figure 9.** (**a**) Composition of ventilation systems before and after improvement of MDU E; (**b**) Ventilation system input and simulation calculation results before and after improvement of ECO2 simulation MDU E.

For ventilation systems, total heat exchangers were applied to E, F, and M complexes. J and P complexes were excluded since they had already applied total heat exchangers (ERV) [48] with higher heat recovery efficiency than the ventilation systems of new energy-saving MDUs. Before improvement, the E complex applied an 'underfloor air distribution system', the F complex used a total heat exchanger (ERV) with a heat recovery rate of heating 72% and cooling 45%, and the M complex used a total heat exchanger (ERV) with air flow rates of 200 cmh and 300 cmh, twice as high as those of ERVs in new energy saving MDUs. By comparing before and after the improvements using the ECO2 program, the average primary energy consumption reduction per unit area per year was found to be 18.7 kWh/m$^2$y, as shown in Table 6.

**Table 6.** Changes in energy demand and energy consumption of E, F, J, M, and P MDU complexes before and after ventilation system improvement.

| Improvement Status | MDU | Energy Demand per Unit Area per Year (kWh/m$^2$ y) | Energy Consumption per Unit Area per Year (kWh/m$^2$ y) | Primary Energy Consumption per Unit Area per Year (kWh/m$^2$ y) |
|---|---|---|---|---|
| Before | E | 118.2 | 155.2 | 158.8 |
| | F | 102.6 | 158.3 | 168.3 |
| | M | 119.3 | 150.8 | 147.6 |
| | Average | 113.4 | 154.8 | 158.2 |
| After | E | 91.8 | 122.4 | 132.4 |
| | F | 101.3 | 154.6 | 162.1 |
| | M | 92.9 | 119.3 | 124.0 |
| | Average | 95.3 | 132.1 | 139.5 |

### 4.2.4. Effect of New and Renewable System

Among 10 MDU complexes that obtained building energy efficiency Grade 1+ or higher in 2021, 9 complexes installed solar PV modules on the roof. On the other hand, new and renewable systems were not applied to all of the standard model E, F, J, M, and P complexes before the improvement. For analysis of the application of the new and renewable systems, it was assumed that solar PV modules were installed on the roof by referring to the application status of 9 new energy-saving MDU complexes [47–49].

The average solar module capacity applied to the new energy saving MDU was a horizontal type with a nominal power output of 455 W per module. Available area for PV installation on the roof for each building of E, F, J, M, and P complexes for ECO2 simulation was calculated under the assumption that no other facilities existed on the roof [47–49].

Among E, F, J, M, and P complexes, the F complex showed best energy performance when solar PV system was installed, as shown in Figure 10, with primary energy consumption reduction per unit area per year of 2.5 kWh/m$^2$y according to ECO2 simulation. In addition, by adoption of solar PV system the average primary energy consumption reduction per unit area per year of E, F, J, M, and P complexes was 2.3 kWh/m$^2$y, as shown in Table 7.

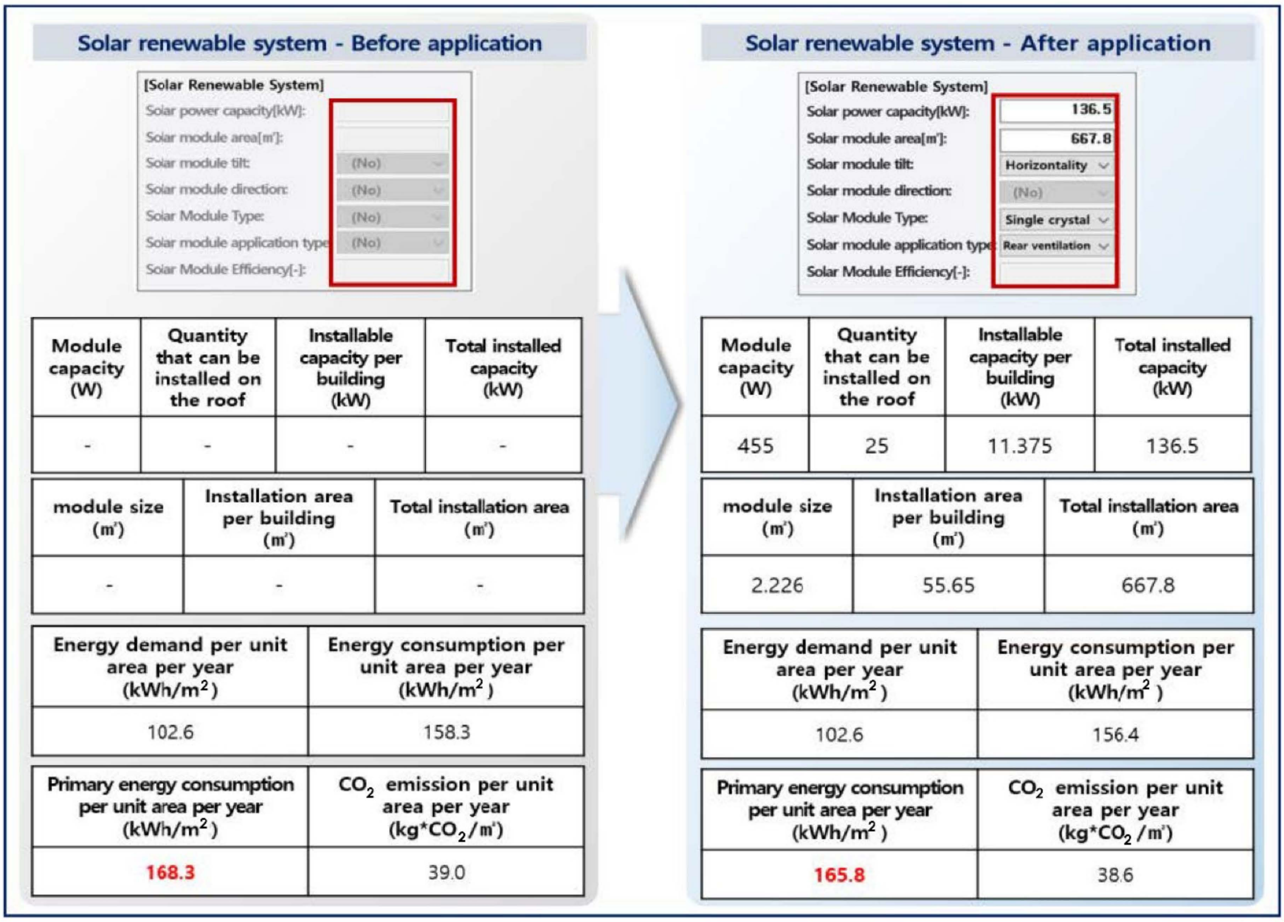



**Figure 10.** Input and simulation results of ECO2 before and after application of solar PV renewable system in MDU F.

**Table 7.** Changes in energy demand and energy consumption of E, F, J, M, and P MDU complexes before and after solar PV system application.

| Improvement Status | MDU | Energy Demand per Unit Area per Year (kWh/m$^2$ y) | Energy Consumption per Unit Area per Year (kWh/m$^2$ y) | Primary Energy Consumption per Unit Area per Year (kWh/m$^2$ y) |
|---|---|---|---|---|
| Before | E | 118.2 | 155.2 | 158.8 |
| | F | 102.6 | 158.3 | 168.3 |
| | J | 92.7 | 121.9 | 137.5 |
| | M | 119.3 | 150.8 | 147.6 |
| | P | 96.5 | 145.5 | 143.3 |
| | Average | 105.9 | 146.3 | 151.1 |
| After | E | 118.2 | 155.2 | 156.6 |
| | F | 102.6 | 158.3 | 165.8 |
| | J | 92.7 | 121.9 | 135.2 |
| | M | 119.3 | 150.8 | 145.2 |
| | P | 96.5 | 145.5 | 141.4 |
| | Average | 105.9 | 146.3 | 148.8 |

The effect of improving energy demand, energy consumption, and primary energy consumption by exterior wall-insulation material, window, ventilation system, and solar PV renewable systems showed a different energy saving effect for each improvement element.

The factor with the highest reduction in primary energy consumption per unit area per year was the improvement of the ventilation system.

*4.3. Selection and Verification of Optimal Improvement Factors*

Figure 11 shows primary energy consumption per area per year after implementing four factors (exterior wall insulation material, windows, ventilation system, and solar PV renewable system) to E, F, J, M, and P complexes using the ECO2 program. Among the four factors, window and ventilation system improvement showed the best energy saving results. Thus, these two factors were selected as the optimal improvement factors. The energy saving effect of applying these two improvement factors simultaneously was further analyzed. In addition, for standard E, F, J, M, and P MDU complexes, it was determined whether the improvement satisfied 20% improvement of energy consumption, which is required to satisfy the criteria for Green Building Certification [50–52].

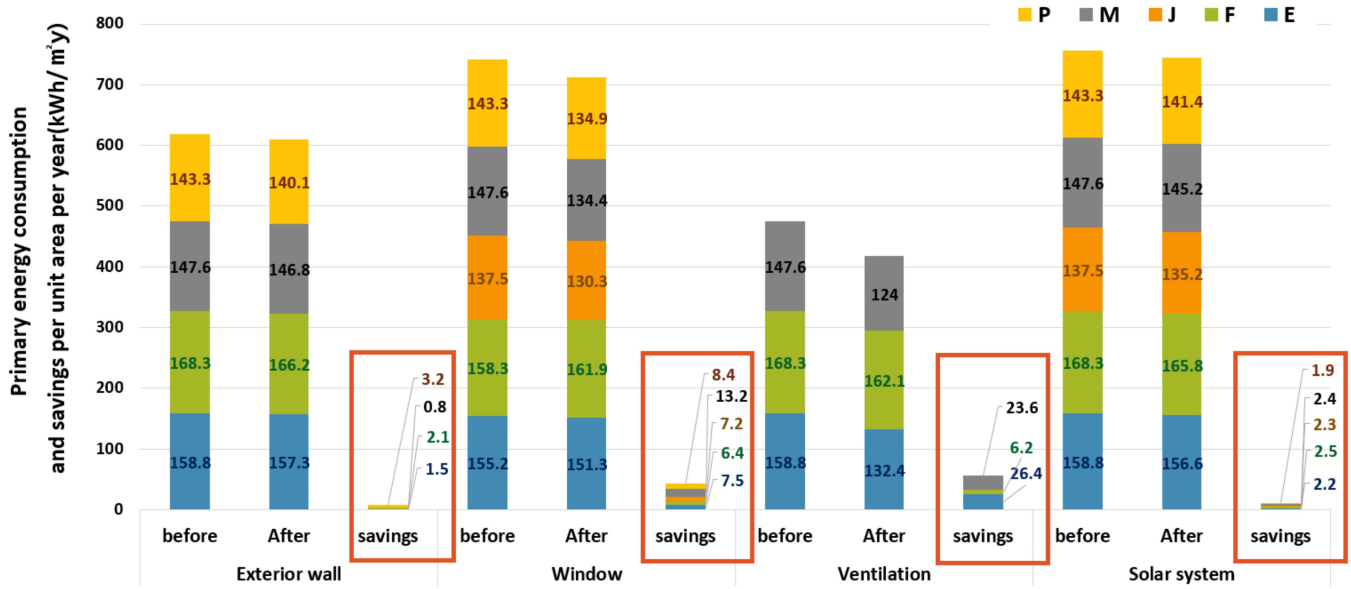



**Figure 11.** Reduction in primary energy consumption per unit area per year by four improvement factors ($kWh/m^2y$).

4.3.1. Improvement Effect by Applying the Optimal Improvement Factor

Figure 12 shows the improvement rate of energy demand and primary energy consumption per unit area per year by application of windows and ventilation facilities, which were selected as the optimal improvement factors. By applying improved ventilation systems, energy demand per unit area per year was reduced by 28.8% in the E complex. By applying improved windows, energy demand per unit area per year was reduced by 14.5% in the M complex.

When both improved window and ventilation system were simultaneously applied to E, F, and M MDUs, average primary energy consumption reduction per unit area per year became 26.6 $kWh/m^2y$, as shown in Table 8.

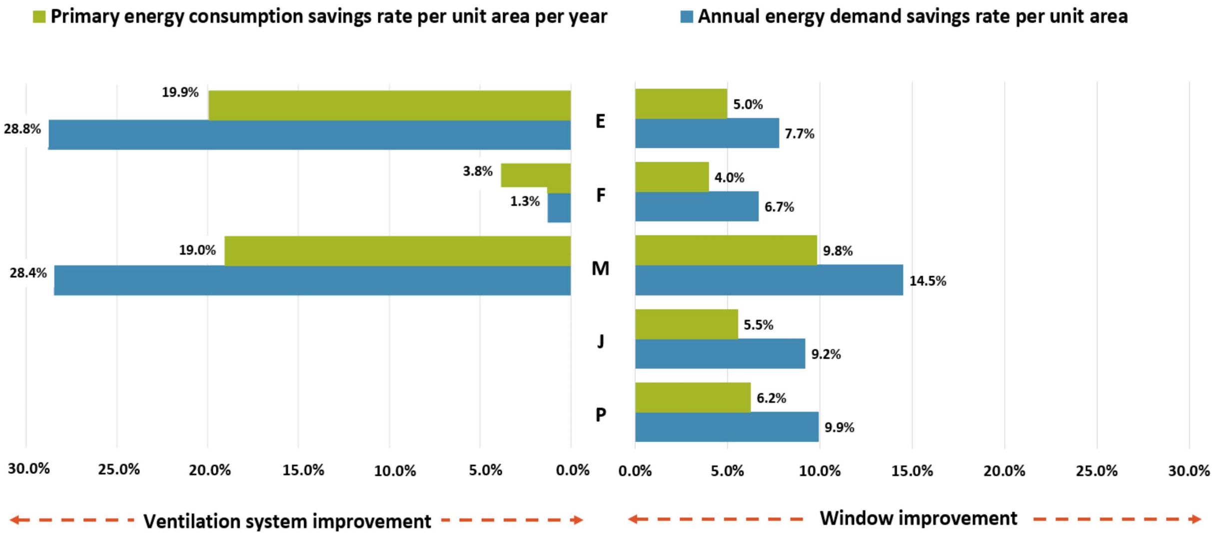



**Figure 12.** Improvement rate (%) of primary energy consumption per area per year and energy demand per unit area, after simultaneous application of window and ventilation system improvements.

**Table 8.** Changes in energy demand, energy consumption and primary energy consumption of E, F, and M MDU complexes before and after window and ventilation system improvement.

| Improvement Status | MDU | Energy Demand per Unit Area per Year (kWh/m$^2$ y) | Energy Consumption per Unit Area per Year (kWh/m$^2$ y) | Primary Energy Consumption per Unit Area per Year (kWh/m$^2$ y) |
|---|---|---|---|---|
| Before | E | 118.2 | 155.2 | 158.8 |
| | F | 102.6 | 158.3 | 168.3 |
| | M | 119.3 | 150.8 | 147.6 |
| | Average | 113.4 | 154.8 | 158.2 |
| After (Window and ventilation system) | E | 83.8 | 112.6 | 125.2 |
| | F | 94.3 | 145.3 | 155.2 |
| | M | 78.9 | 102.3 | 111.4 |
| | Average | 85.7 | 120.1 | 131.6 |

The reduction rate of primary energy consumption and the change in building energy efficiency rating after the simultaneous improvement of windows and ventilation systems can be viewed in Figure 13. The building energy efficiency rating of the E and M complexes was improved by one grade, and the primary energy consumption per unit area per year reduction rates were 26.8% for the E complex and 32.5% for the M complex. Complexes M and E met the condition of improving primary energy consumption by 20% per unit area per year, which is the standard for green building conversion in the 'Energy Performance Improvement Standard for Existing Buildings' [50].


**Figure 13.** The reduction rate of primary energy consumption per unit area per year and changes in building energy efficiency ratings, due to improvements in windows and ventilation systems.

4.3.2. Examples of Calibration through Verification

Comparison with the actual measurement results for heating energy consumption and ventilation energy consumption was carried out, to assess the reliability of the ECO2 simulation results for analyzing the improvement effect of windows and ventilation systems. Analysis showed these to be the most effective factors. Correction work was done to improve the reliability of the simulation results [53–56].

First, heating energy consumption before and after improvement were corrected as shown in Table 9, using 'Comparison of heating energy consumption and actual usage in MDU by the Building Energy Efficiency Rating Program' [55].

**Table 9.** Results of applying the heating energy correction factor suggested in 'Comparison of heating energy consumption and actual consumption of MDU by the Building Energy Efficiency Rating Program' (application of the correction factor for the central region).

| Improvement Status | MDU | Correction Factor for Heating | Primary Energy Consumption per Unit Area per Year (kWh/m$^2$ y) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Heating | Heating | Lighting | Ventilation | Sum |
| Before | E | 0.5 | 36.15 | 28.7 | 41.0 | 16.9 | 122.75 |
| | F | | 38.55 | 26.3 | 46.8 | 18.1 | 129.75 |
| | M | | 35.2 | 29.0 | 33.9 | 14.3 | 112.40 |
| After | E | 0.5 | 20.75 | 28.8 | 41.0 | 13.9 | 104.45 |
| | F | | 34.4 | 26.3 | 46.8 | 13.3 | 120.80 |
| | M | | 17.4 | 29.0 | 33.9 | 13.7 | 94.00 |

Second, to improve the reliability of the ECO2 analysis results for the application of total heat exchangers, the energy consumption was derived by changing the total heat exchangers applied in the study to natural ventilation. This was done by following the methodology in 'Comparative Analysis of Energy Performance by Ventilation Systems in MDUs' [56]. A correction factor of 4.22% was chosen to correct primary energy consumption of ventilation [56]. Table 10 shows the results of the primary energy consumption per unit area per year of E, F, M complexes, applying both the first heating energy correction factor and the second ventilation system correction factor.

**Table 10.** Results of the correction of the primary energy consumption of the final E, F, and M complexes, applying the heating coefficient correction and the ventilation system correction factors.

| Improvement Status | MDU | Primary Energy Consumption per Unit Area per Year (kWh/m$^2$y) [Table 8] | After Correction | |
|---|---|---|---|---|
| | | | Correction Factor | Primary Energy Consumption per Unit Area per Year (kWh/m$^2$y) |
| Before | E | 122.75 | +4.22% | 127.93 |
| | F | 129.75 | | 135.22 |
| | M | 112.40 | | 117.14 |
| After | E | 104.45 | +4.22% | 108.86 |
| | F | 120.80 | | 125.90 |
| | M | 94.00 | | 97.97 |

Average primary energy consumption per unit area per year of E, F, M complexes before correction was 131.6 kWh/m$^2$y. After applying corrections as suggested in [55,56], the value became 110.9 kWh/m$^2$y. As the next stage of the study process, economic analysis was carried out.

## 5. Economic Analysis

To study the economic burden on users, the effects of windows and ventilation systems, which were selected as the optimal improvement factors, on annual energy cost and life cycle cost were analyzed [57–59]. For economic analysis of heating and electricity energy cost, 84 $m^2$ of complex M, which showed the highest cost reduction after improvement, was analyzed. For life cycle cost analysis, annuity present value analysis was conducted using only energy cost [57–59].

*5.1. Annual Energy Usage Fee Analysis*

The annual energy cost analysis used district heating fuel consumption and electricity consumption derived from the ECO2 simulation. Primary energy consumption per unit area per year using district heating can be calculated by Equation (1).

$$\dot{E}_{pec,dh} = 0.728 \cdot E_{dh} \cdot \frac{1}{A_{MDU}} \quad (1)$$

The variables in Equation (1) are defined as follows:
$\dot{E}_{ped,dh}$: Annual primary energy consumption per unit area per year (kWh/$m^2$y)
0.728: Primary energy conversion factor for district heating (-)
$E_{dh}$: Annual district heating energy consumption (kWh/y)
$A_{MDU}$: Total floor area of the MDU ($m^2$)
Primary energy consumption per unit area per year using electricity can be calculated by Equation (2).

$$\dot{E}_{pec,p} = 2.75 \cdot E_p \cdot \frac{1}{A_{MDU}} \quad (2)$$

The variables in Equation (2) are defined as follows:
$\dot{E}_{ped,p}$: Annual primary energy consumption per unit area per year (kWh/$m^2$y)
2.75: Primary energy conversion factor for electricity (-)
$E_p$: Annual power energy consumption (kWh/y)
$A_{MDU}$: Total floor area of the MDU ($m^2$)
Energy cost can be calculated with Equations (3) and (4). Cost of district heating energy can be calculated with Equation (3).

$$C_{dh} = \left(0.86 \cdot 0.053 \cdot \dot{E}_{ped,\ dh}\ A_h\right) 1.1 \quad (3)$$

The variables in Equation (3) are defined as follows:
$C_{dh}$: District heating energy cost ($)
0.86: Unit conversion factor (Mcal/kWh)
0.053: Unit cost of district heating energy ($/Mcal)
$\dot{E}_{ped,dh}$: Annual primary energy consumption per unit area per year (kWh/$m^2$y)
$A_h$: Floor area of house ($m^2$)
1.1: Basic fee additional factor (-)
Cost of electricity can be calculated with Equation (4).

$$C_p = \left(0.082 \cdot \dot{E}_{ped,\ p} \cdot A_h\right) + 0.758 \quad (4)$$

The variables in Equation (4) are defined as follows:
$C_p$: Electricity cost ($)
0.082: Unit cost of electricity ($/kWh)
$\dot{E}_{ped,p}$: Annual primary energy consumption per unit area per year (kWh/$m^2$y)
$A_h$: Floor area of house ($m^2$)
0.758: Basic cost additional factor ($)
Energy cost by primary energy consumption per unit area per year before and after improvement of the M complex was analyzed, as shown in Table 11 [60–62].

**Table 11.** Energy cost of district heating energy and electricity for the M complex before and after improvement. (Currency: 1$≒1200 KRW, as of 7 January 2022).

| Complex | Improvement Status | Corrected Primary Energy Consumption per Unit Area per Year (kWh/m²y) | | | Type (m²) | District Heating Energy Cost ($/m²y) | Electricity Cost ($/m²y) | Sum ($/m²y) |
|---|---|---|---|---|---|---|---|---|
| | | District Heating Energy | Electricity | Sum | | | | |
| M | Before | 35.4 | 16.1 | 51.5 | 59 | 104 | 78.3 | 182.3 |
| | | | | | 74 | 130.4 | 98.1 | 228.5 |
| | | | | | 84 | 148.0 | 111.2 | 259.2 |
| | After | 17.2 | 15.2 | 32.4 | 59 | 50.4 | 74.0 | 124.4 |
| | | | | | 74 | 63.2 | 92.6 | 155.9 |
| | | | | | 84 | 71.8 | 105.1 | 176.8 |

Cost analysis based on primary energy consumption of heating and ventilation was carried out by referring to the heat cost table of the 'Korea District Heating Corporation' and electricity cost calculation standards of the 'Korea Electric Power Corporation' [60–62]. As a result, the 84 m² type was calculated to return an annual profit of $82.9 if improvements were implemented.

## 5.2. Life Cycle Cost Analysis

Life cycle cost analysis was performed for 30 years of operation with implementation of energy saving windows and ventilation systems. Future costs were converted to present costs using a 'present value method' that considers annual cost increase. Annual energy cost increase of gas and electricity was assumed to be 1.53%, which was derived considering consumer price increase during 2012–2021 [57–59,63].

Annuity present value coefficient can be derived with Equation (5).

$$F_C = \frac{(1 + 0.0153)^n - 1}{0.0153(1 + 0.0153)^n} \quad (5)$$

Variables in Equation (5) are defined as follows:

$F_C$: Electricity cost ($)

0.0153: Average consumer price inflation rate from 2012 to 2021 (-)

In order to include construction cost to life cycle cost analysis when applying window and total heat exchanger improvements, product and construction costs of Companies A and B were collected. Product and installation costs are shown in Table 12.

**Table 12.** Window and total heat exchanger installation and product costs. (Currency: 1$≒1200 KRW, As of 7 January 2022).

| Improvement Factors | Type, Air Flow Rate | Product Price ($) | Installation Cost ($) | Total Cost ($) |
|---|---|---|---|---|
| Ventilation | 59 m², 100 cmh | 500 | 2608 | 3108 |
| | 74 m², 150 cmh | 583 | 2781 | 3364 |
| | 84 m², 150 cmh | 583 | 3090 | 3673 |
| Window | 59 m² | 5898 | 500 | 6398 |
| | 74 m² | 7115 | 583 | 7698 |
| | 84 m² | 7068 | 667 | 7735 |

Based on M complex, profits for 30 years of use became $1385, $1736 and $1970 for types 59 m², 74 m², and 84 m², respectively. As a result, it was confirmed that the construction costs were greater than the profit from energy saving (Table 13) [57–59,64].

**Table 13.** Reflecting an average inflation rate of 1.53% for 2012–2021, life cycle cost analysis using annuity present value factor for 30 years. (Currency: 1$≒1200 KRW, as of 7 January 2022).

| Type | Annuity Present Value Factor | Annual Profit with Improvement ($) | Profit ($) (30 Years of Use) |
|---|---|---|---|
| 59 $m^2$ | 23.914 | 57.9 | 1385 |
| 74 $m^2$ | | 72.6 | 1736 |
| 84 $m^2$ | | 82.4 | 1970 |

Table 14 shows the results of life cycle cost analysis reflecting the sharply increased inflation rate of 4.8% as of April 2022 [65]. As shown in Table 14, the energy saving benefits for 59 $m^2$, 74 $m^2$, and 84 $m^2$ were $911, $1142, and $1296, respectively.

**Table 14.** Reflecting the inflation rate of 4.8% as of April 2022, life cycle cost analysis using annuity present value factor for 30 years. (Currency: 1$≒1200 KRW, as of 7 January 2022).

| Type | Annuity Present Value Factor | Annual Profit with Improvement ($) | Profit ($) (30 Years of Use) |
|---|---|---|---|
| 59 $m^2$ | 15.729 | 57.9 | 911 |
| 74 $m^2$ | | 72.6 | 1142 |
| 84 $m^2$ | | 82.4 | 1296 |

## 6. Discussion

In this study, energy improvement factors and economic feasibility were analyzed for MDUs in the metropolitan areas of Korea, which account for 33% of the total energy consumption by buildings in 2020. This study was conducted on 46 MDU complexes that have obtained domestic building energy efficiency rating certification. Four factors were used to derive a standard apartment complex: (1) applied household type, (2) average exterior wall insulation and window performance, (3) average energy consumption and demand per unit area per year, (4) average applied facility system, and (5) average monthly energy demand per unit area. In the case of deriving improvement factors, 10 MDU complexes that recently acquired a building energy efficiency rating above Grade 1+ were targeted. Primary energy consumption comparison analysis and economic feasibility analysis were conducted by applying the improvement factors to the standard MDU complexes using the ECO2 program.

This study is a case study applied to domestic MDU complexes, and is limited in the extent to which it can reflect various renewable energy systems [66–68]. Using present value method economic analysis, this study has found a limit to the profit obtained only from energy saving when compared to construction costs [67,68]. Therefore, future studies are necessary to analyse diverse renewable energy systems, and it is important that their calculations include change in asset values after improvements are made.

## 7. Conclusions

In this study, analysis was conducted by using ECO2, a building energy efficiency rating program, to present improvement factors for MDU complexes with high energy consumption in the metropolitan areas of Korea, to reduce the economic burden on users. Factor effects and energy costs were analyzed; in particular, standard complexes were identified, by analyzing buildings with building energy efficiency ratings from 2014 to 2015, and energy improvement factors were derived by analyzing buildings that obtained building energy efficiency ratings of Grade 1+ or higher in 2021 after the strengthening of domestic building energy standards. By applying the improvement factors to the standard complex, the energy cost was derived from the primary energy consumption before and after the improvement of the ECO2 program results. Life cycle cost analysis was also carried out, using the present value method.

(1) As a result of analyzing 46 MDU complexes that obtained building energy efficiency rating certification from 2014 to 2015, the average energy demand per unit area per year was found to be 107.5 kWh/m$^2$, the average energy consumption per unit area per year was 146.5 kWh/m$^2$, the average primary energy consumption per unit area per year was 150.7 kWh/m$^2$. The building energy efficiency rating was analyzed to correspond to an average of Grade 2.
(2) The monthly heating energy requirement per unit area was analyzed, revealing that the monthly average heating energy demand of new energy saving MDUs in 2021 was reduced by 1.7 kWh/m$^2$y compared to MDUs certified in 2014–2015.
(3) As a result of analyzing the primary energy consumption reduction rate due to the simultaneous improvement of windows and ventilation systems, the building energy efficiency ratings of E and M complexes were improved by one grade. The reduction rate of primary energy consumption was analyzed as 26.8% for E complex and 32.5% for M complex.
(4) As a result of life cycle cost analysis using the present value method for 30 years, it was confirmed that a profit of $1384.6~$1970.5 was acquired for M complex, which had undergone simultaneous improvement of the windows and ventilation system.

In this study, life cycle cost analysis for energy consumption was presented; for future research, we plan to include demolition costs as well as product and construction costs. Furthermore, to improve life cycle analysis, we plan to continue research on increases in asset costs if improvements are implemented.

**Author Contributions:** Conceptualization, K.-W.L.; methodology, K.-W.L.; experiment, K.-W.L.; software, K.-W.L.; validation, Y.I.K.; formal analysis, K.-W.L.; investigation, K.-W.L.; resources, K.-W.L.; data curation, K.-W.L.; writing—original draft preparation, K.-W.L.; writing—review and editing, Y.I.K.; visualization, K.-W.L.; supervision, Y.I.K.; project administration, Y.I.K.; funding acquisition, K.-W.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study was supported by the Research Program funded by the SeoulTech (Seoul National University of Science and Technology).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

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

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