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*Article*

# 3D Visualization Solution to Building Energy Diagnosis for Energy Feedback

**Tae-Keun Oh [1], Donghwan Lee [2], Minsoo Park [3], Gichun Cha [4] and Seunghee Park[5,*]**

[1] Department of Safety Engineering, Incheon National University, 119, Academy-ro, Yeonsu-gu, Incheon, Republic of Korea, 22012; tkoh@inu.ac.kr
[2] Department of Convergence Engineering for Future City, Sungkyunkwan University, 2066, Seobu-ro, Suwon-si, Gyeonggi, Republic of Korea, 16419; ycleedh@paran.com
[3] Department of Civil, Architectural and Environmental System Engineering, Sungkyunkwan University, 2066, Seobu-ro, Suwon-si, Gyeonggi, Republic of Korea, 16419; pmskku@naver.com
[4] Department of Convergence Engineering for Future City, Sungkyunkwan University, 2066, Seobu-ro, Suwon-si, Gyeonggi, Republic of Korea, 16419; ckckicun@naver.com
[5] School of Civil, Architectural Engineering and Landscape Architecture Sungkyunkwan University, 2066, Seobu-ro, Suwon-si, Gyeonggi, Republic of Korea, 16419; shparkpc@gmail.com
* Correspondence: shparkpc@gmail.com; Tel.: +82-31-290-7525

**Abstract:** Owing to the large ratio of consumption in the building sector, energy saving strategies are required. Energy feedback is an energy-saving strategy that consumers to change their energy-consumption behaviors. The strategy has been principally focused on providing energy-consumption information. However, realization of energy savings using only consumption information remains limited. In this paper, a building-energy three-dimensional (3D) visualization solution is thus proposed. This solution includes the process of diagnosing a building and providing prediction of energy requirements if a building improvement is undertaken. Accurate diagnostic information is provided by real-time measurement data from sensors and building models using a close-range photogrammetry (CRP) method without depending on blueprints. The information is provided by employing visualization effects to increase the energy-feedback efficiency. The proposed strategy is implemented on two testbeds, and building diagnostics are performed accordingly. For the first testbed, the predicted energy improvement amount resulting from the facility upgrade is provided. The second testbed is provided with a 3D visualization of the energy information. The aim is to determine if the building manager will replace the facility after our recommendation is given to improve the building energy efficiency driven from the energy information. Unlike existing systems, which provide only ambiguous data that lack quantitative information, this study is meaningful because it provides energy information with the aid of visualization effects before and after building improvements.

**Keywords:** Energy diagnosis; Close-range photogrammetry; Energy efficiency; Visualization of information; Energy feedback

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## 1. Introduction

In recent years, the expansion of power access and the industrialization and urbanization of China and India have led to a 30% increase in the energy demand forecast by 2040 [1]. Energy-intensive countries such as those that are members of the Organization for Economic Co-operation and Development (OECD), are striving to reduce their dependence on fossil energy, shift to renewable energies, and improve energy efficiencies. However, the primary energy share of fossil fuels is more than 70% and is expected to increase steadily [1-2]. As a result, the global increase in greenhouse gas emissions has led to abnormal weather phenomena in each region of the world,

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causing difficulties in coping with disasters and increasing the frequency and magnitude of natural disasters related to climate [3-5].

Much of the energy produced is consumed in buildings, typically in the United States (US) and European Union (EU), with buildings accounting for more than 40% of the energy consumption. [6-7]. This finding indicates that energy consumption in buildings has a direct effect on greenhouse gas emissions. As a result, focus on its management is required and various method are suggested by advance studies to solve the problem. [8-12] In addition, since the proportion of obsolete buildings around the world is increasing and because older buildings have up to eight times the amount of energy needed per square meter per year compared to new buildings, the overall consumption is increasing [13]. Moreover, the energy consumption of older buildings is expected to increase even further. Energy efficiency retrofit (EER) is a process that can reduce energy consumption and greenhouse gas emissions through improvements to existing buildings. Various studies using EER have performed energy efficiency diagnosis for the purpose of increasing energy savings in buildings. This phenomenon indicates that building energy diagnosis has become an important issue [14-15].

Furthermore, so-called energy feedback or eco-feedback is an energy strategy that focuses on solving the fundamental problem of energy saving and providing information to residents and property owners to foster energy-consumption behavioral changes. The American Council for Energy Efficient Economy (ACEEE) reported that savings of more than 10% are achieved when energy feedback is provided. Research is underway to realize these savings by applying the energy feedback strategy [16-18]. Since monthly utility bills are the main source of energy consumption information for users, the central idea of previous studies was to improve the visual effect of these bills to enable user awareness and to change [19-20].

To effectively realize energy savings, the main issue has been determining the most effective means of communicating energy use [21]. Psychological literature suggests that visualizing information results in increased attention to the information, [22] and thereby motivating people in accordance with the goal of the visual material [23]. Nevertheless, most energy feedback currently provided is in the form of monthly bills that lack data visualization [19]. Therefore, the present research was conducted with consideration of visualizing information for a building depending on the user initiative to improve the building energy efficiency.

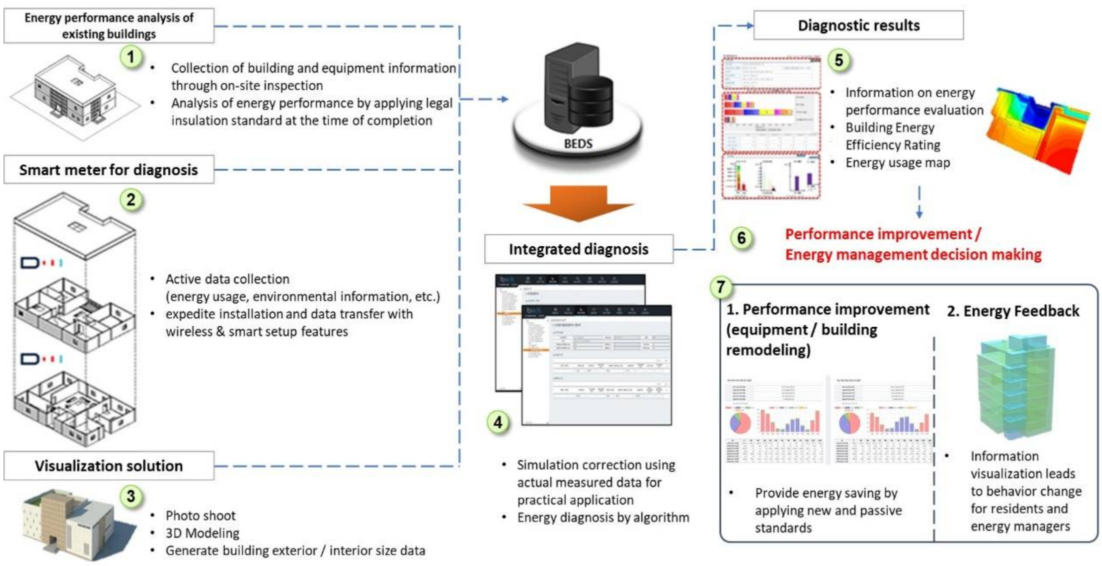


**Figure 1.** Integrated diagnosis algorithm process of building energy conservation

To improve building energy efficiency, we developed in this study a building energy diagnosis visualization solution. The solution is intended to provide actionable information for users. The detailed process for achieving the objective of the visualization solution is outlined as follows: 1) Perform building energy diagnosis for existing buildings that are expected to have low efficiency. 2) input diagnostic data into an energy simulation program for showing the amount of energy that can

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be saved if specific elements are improved 3) Develop a building-energy three-dimensional (3D) visualization solution to efficiently provide the given information (Figure 1.).

## 2. Research Method

The present research has two objectives: developing a building-energy diagnosis system to improve energy efficiency and designing a solution that visualizes the measured information in the process. The whole process is divided into 1) a process for providing diagnosis results and 2) a building energy visualization process. In the process of the building-energy diagnosis, the energy performance is analyzed using information from the existing building and equipment as input (smart meters etc.). The results of the analyses are provided in graph format. The smart meter is used for diagnosis to acquire energy usage information and environmental information. The energy performance improvement is predicted with the aid of an energy simulation program. The next task is an building energy feedback provision. First, the building shape model is constructed using close-range photogrammetry (CRP). Second, the acquired energy information from the smart meter is linked with each zone of the building. Finally, the information is provided to the user after information grouping and coloring according to the energy consumption status of each zone is determined.

### *2.1. Energy Efficieny Diagnosis*

To improve building energy efficiency, various systems have been implemented worldwide to evaluate building energy consumption. In Europe, buildings have been managed since 2002 by the Energy Performance of Building Directives (EPBD), which serves to improve building-energy systems. In the US, Standard 90.1 of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is used for building energy evaluations. Moreover, various systems have been developed by the society [24]. Meanwhile, the Republic of Korea finances and manages the Energy Efficiency Grade Certification System, which can quantitatively evaluate the energy performances of buildings. According to the system, the energy efficiency grade is calculated by multiplying the energy required for heating, cooling, and hot water supply per square meter of the building by their corresponding primary energy conversion factors [25-26]. Table 1, ten energy-efficiency classes (ranging from 1 +++ to 7), which are classified according to annual primary energy per unit area

**Table 1.** Energy efficiency grading system.

| Rating | Residential building<br>Annual primary energy per unit area<br>($kWh/m^2 \cdot year$) | Non-residential building<br>Annual primary energy per unit area<br>($kWh/m^2 \cdot year$) |
|---|---|---|
| 1+++ | Less than 60 | Less than 80 |
| 1++ | More than 60 less than 90 | More than 80 less than 140 |
| 1+ | More than 90 less than 120 | More than 140 less than 200 |
| 1 | More than 120 less than 150 | More than 200 less than 260 |
| 2 | More than 150 less than 190 | More than 260 less than 320 |
| 3 | More than 190 less than 230 | More than 320 less than 380 |
| 4 | More than 230 less than 270 | More than 380 less than 450 |
| 5 | More than 270 less than 320 | More than 450 less than 520 |
| 6 | More than 320 less than 370 | More than 520 less than 610 |
| 7 | More than 370 less than 420 | More than 610 less than 700 |

Although differences exist in building energy evaluation methods or regulations depending on the environment of each country and region, generally they are focused on reducing energy usage

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and emissions. The present research was conducted on buildings located in the Republic of Korea and the efficiency level was determined according to the Republic of Korea management grade. The diagnoses of buildings were conducted according to the following process:

- Collect building and facility information through on-site inspection.
- Calculate the energy demand energy of an existing building using its structural data (Table 2) as input
- Calculate the final building energy. This task is performed by first obtaining the heating and cooling data of the facility and then calibrating them with consideration of the actual energy usage which is measured by the diagnostic smart meter (Figure 2.).
- Obtain the building final energy data after applying the conversion factor to the primary energy and then assign a building energy efficiency rating according to grading system.
- Recalculate the building-energy demand after enacting the building-energy efficiency improvement scenarios to produce an improved rating.

Demand energy(DE) is the energy required by the building to maintain its interior livability (e.g., building thermal environment). It is primarily affected by the building area, heating types, and cooling systems. Final energy (FE) is the energy required to meet fulfill the building demand plus the energy lost through the building facility on account of the low-quality equipment installed in the building. Primary energy(PE) is the fossil energy needed to meet FE. Of all three types, it has the greatest impact on climate change [27-35].

Generally speaking, obsolete or low energy efficiency buildings require a large amount of PE in Europe. For instance, 35% of the buildings are more than 50 years of age, and therefore need to improve their energy efficiency through diagnoses [18]. In this work, we conducted energy diagnostics on buildings requiring such improvements

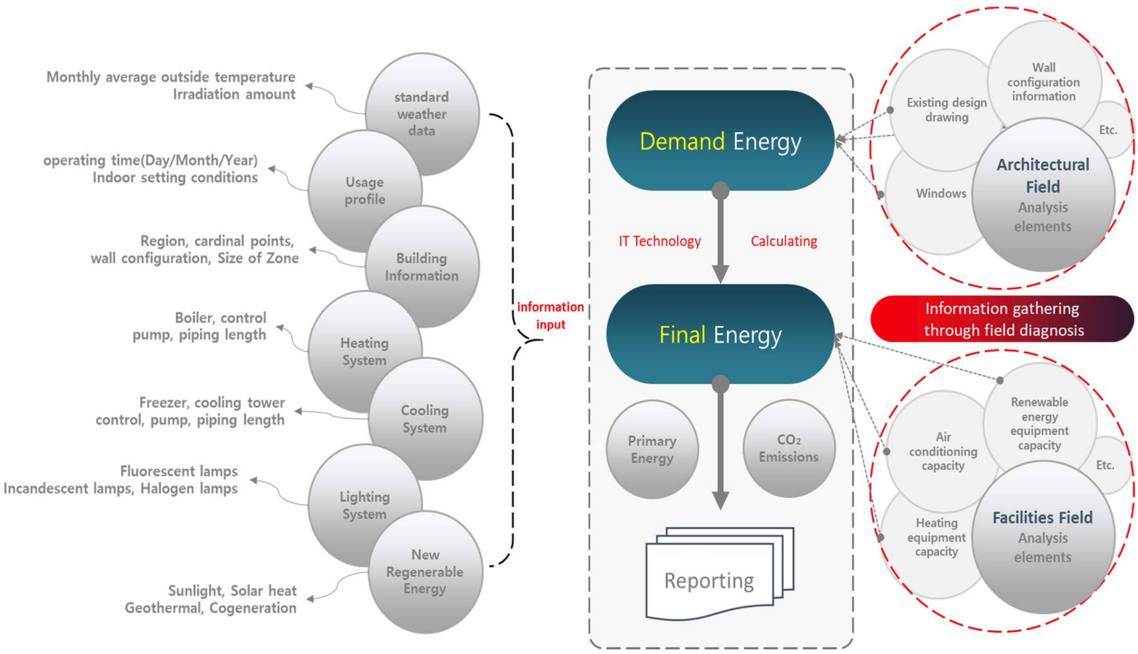


**Figure 2.** Principle of calculation of energy demand and final energy.

**Table 2.** Data used for diagnosis algorithm.

| Field | Division | Item |
|---|---|---|
| Architecture | Architectural basic information | Building name, Location, Area, Bearing, Address, Floor |
| | Architectural details | Wall Insulation type, Wall heat storage capacity, Night operation type, Weekend operation type, Heating method, Cooling method, Air leakage rate, Presence or absence of Out air control(OAC), Presence of absence of heat recovery ventilators, Light power density |
| | Wall windows Information | Bearing, Wall area, Wall color, Window & door area |
| Facilities (Heat source equipment) | Basic information | Use of heat source equipment, Heat source equipment type, Hot water supply temperature, Return water temperature |
| | Boiler | Boiler type, Boiler operation method, Fuel used, Boiler rated output, Boiler efficiency, District heating type, Heat exchanger output, Heat exchanger efficiency, Rated output of electric boiler, Electric boiler efficiency |
| | Heating circulation pump | Pump power, Pump control type, Weekend operation type |
| | Hot water piping network / Circulation pump | Pump power, Pump control type |
| | Heating supply | Room temperature control method, Control power, pump power, Pump quantity, fan power, fan quantity |
| Facilities (Cooling) Air conditioning equipment information | Basic Information | Refrigerator type, capacity, COP (coefficient of performance) |
| | Compressor freezer setting | Compression system, Scroll compressor control system, Cooling tower type, Coolant inlet temperature, Evaporative cooling tower type |
| | Air conditioning distribution setting | Heat transfer medium, Outlet temperature, Inlet temperature, Temperature difference |
| | Distribution network information | Pump control, Pump power, Piping pressure loss, Individual resistance |
| | Pressure loss type | Refrigerator pressure loss, Equipment pressure loss, Valve pressure loss |
| | Air conditioning distribution piping setup | Number of floors, Width, Length, height |

### *2.2. Energy Simulation*

Building energy simulation refers to the activity of creating energy models using computer-based analysis programs. These serve to evaluate the performance of all or some of the building's systems. There are many energy simulation programs such as ECO2, ECO-CE3 and BESS. However, only ECO-CE3 can compare the states before and after improvement of energy efficiency. Therefore, ECO-CE3 is adopted as a program for this study. ECO-CE3 was a building energy performance evaluation solution based on the EPBD international standard ISO 13790 and Germany's building energy performance evaluation standard DIN V48599. It simulates the problems of the energy performance from the design stage [36]. In addition, it predicts the annual cost of energy and the amount of carbon dioxide emitted. In this study, the energy simulation was used to show the annual energy efficiency improvement of the building on account of improvements in the building performance. If the simulation was not applied, no quantitative information could be provided regarding an energy efficiency increase when improvements were made.

### *2.3. Close-range photogrammetry-based 3D models*

To provide diagnosis information and gather feedback on a building, current spatial information is required because the as-built passive and active data of the target building may have been altered through years of service or the data may not be available at all. CRP is a non-contact technology that is used to determine the 3D geometry (location, size and shape) of an actual object by measuring and analyzing the two-dimensional (2D) ground photographs [37]. The collinearity condition is an essential equation of photogrammetry, it is based on the basic theory that the perspectival center, the image point and the corresponding object point lie on one line [38]. A 3D model is constructed by geometrically establishing the relationship between the 3D object coordinates and the object coordinates of a 2D image through the underlying perspectival system [39].

The advantage of CRP is that it can acquire 3D information of structures in a relatively short time, and it can easily construct a model for a building without requiring an as-built drawing. In addition, its accuracy is high. Many studies have thus used CRP to measure structural deformations [37, 40]. Owing to its accuracy and capacity to work without restrictions make CRP a useful tool for providing intuitive building shape information. In addition, it improves the reliability of the shape and area information of the building which can be fed into the building energy simulation program.

### *2.4. Information Visualization*

Information visualization refers to visualizing data using graphical elements to clearly and effectively the information. There are seven visualization elements: brightness, color, texture, shape, location, direction, and size [41]. Humans can easily distinguish differences in length, shape, orientation, and color without much effort. This ability is referred to as "pre-attentive processing." When information is provided without a visualization function ("attentive processing"), considerable time and effort are required to distinguish the information differences [42]. To provide intuitive and efficient energy information, this study focused on grouping data and linking them to the model, thereby distinguishing them according to their characteristics. The visualization was conducted using color.

## 3. Implementation

### *3.1. Testbeds*

The study testbeds were chosen to reflect a real building-energy management in the Republic of Korea. Of all buildings in Korea, 99.97% are small and medium-sized, and 91% of the total building energy consumption is by these buildings [43]. In addition, for buildings measuring greater than 3,000 square meters, energy use regulations have been implemented through various national and local government policies. However, energy management is not usually implemented in buildings because there are no regulations for buildings having an area less than 3,000 square meters. Therefore, in this study, these classes of buildings requiring energy management were selected as testbeds.

Table 3 illustrates the two testbeds used for energy diagnosis and energy information purposes. Testbed 1 is a business and factory facility located in Ansan City, Gyeonggi Province. It has high base energy consumption owing to production in the factory. Testbed 2 is a business and residential building in Seoul. We evaluated the building energy efficiency level through pre-energy diagnostics for the two testbeds. For testbed 1, we then re-evaluated the energy efficiency after providing a building energy efficiency improvement plan. For testbed 2, we provided real-time energy consumption data to help users realize energy savings.

### *3.2. Build Cloud-based Database*

To perform building-energy diagnosis and build a visualization solution, it is necessary to construct a database for data input to compute the DE and FE. The database comprises the energy consumption amount, environmental data, building spatial information, and equipment data. The database also considers the requirement of login keys to access the energy information webpage so that only the appropriate user can access it. This is because the database is intended to provide information by visualizing it on a webpage instead of in paper format, such as the format of existing monthly bills.

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**Table 3**. Testbed descriptions.

| | Testbed 1 | | Testbed 2 | |
|---|---|---|---|---|
| **Building purpose** | Business Facilities / Neighborhood Facilities | | Business facilities | |
| **Location** | Yeongmal-ro, Eunpyeong-gu, Seoul, Republic of Korea | | Danwon-gu, Ansan-si, Gyeonggi-do, Seoul, Republic of Korea | |
| **Building Area** | **Total floor area**<br>**Number of floors** | 1,889 m²<br>5th floor | **Total floor area**<br>**Number of floors** | 2,517 m²<br>2nd floor |
| | View of the building | Panel board | View of the building | Panel board |
| |  |  |  |  |

We thus implemented the visualization solution on the web and built a cloud-type database for a large number of users (residents and administrators) to enable their access to the webpage. Users for a given building are grouped and provided with an ID unique to that building that is used as a key to access the webpage. The building information table stores each floor and zone usage data, building environment data (humidity, temperature, etc.), and external environment data. A table log is used to store collected hourly data for each floor and zone in chronological order. In addition, data are collected by day, month, and year and used as basic data for energy diagnosis (Figure 3.).

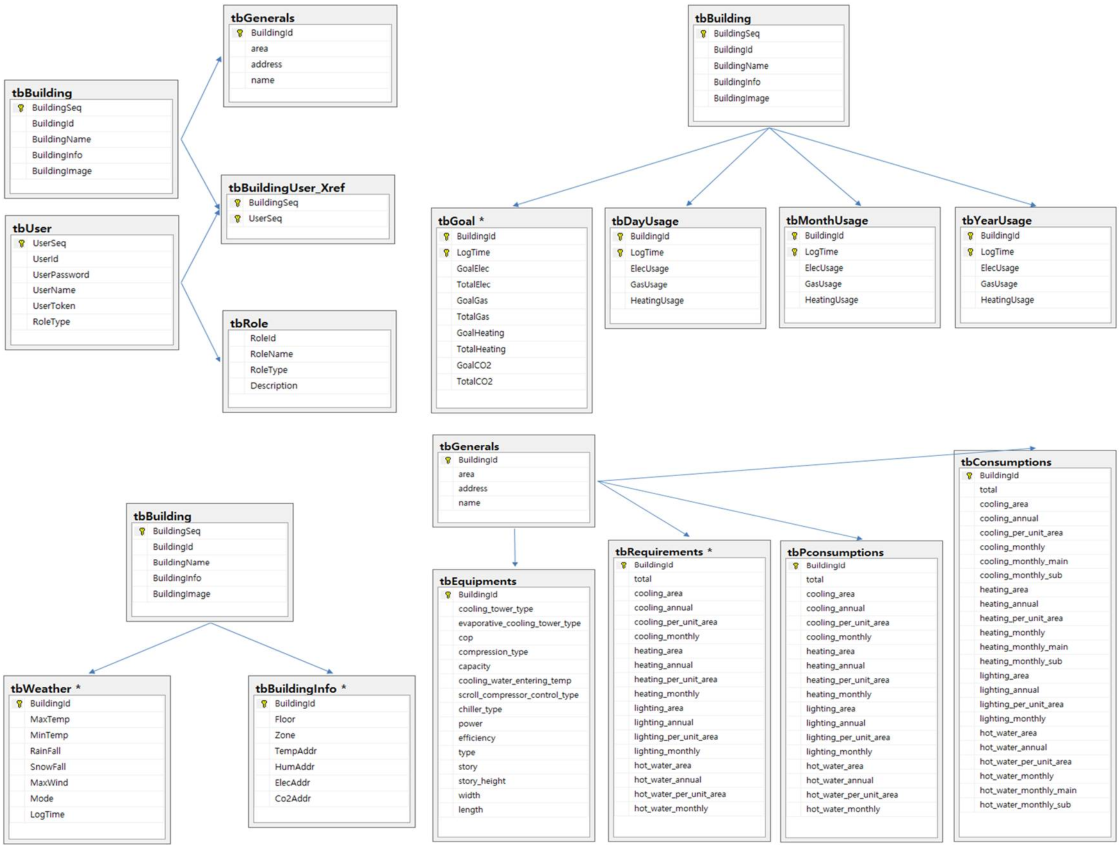


**Figure 3.** Composition of database for energy visualiz

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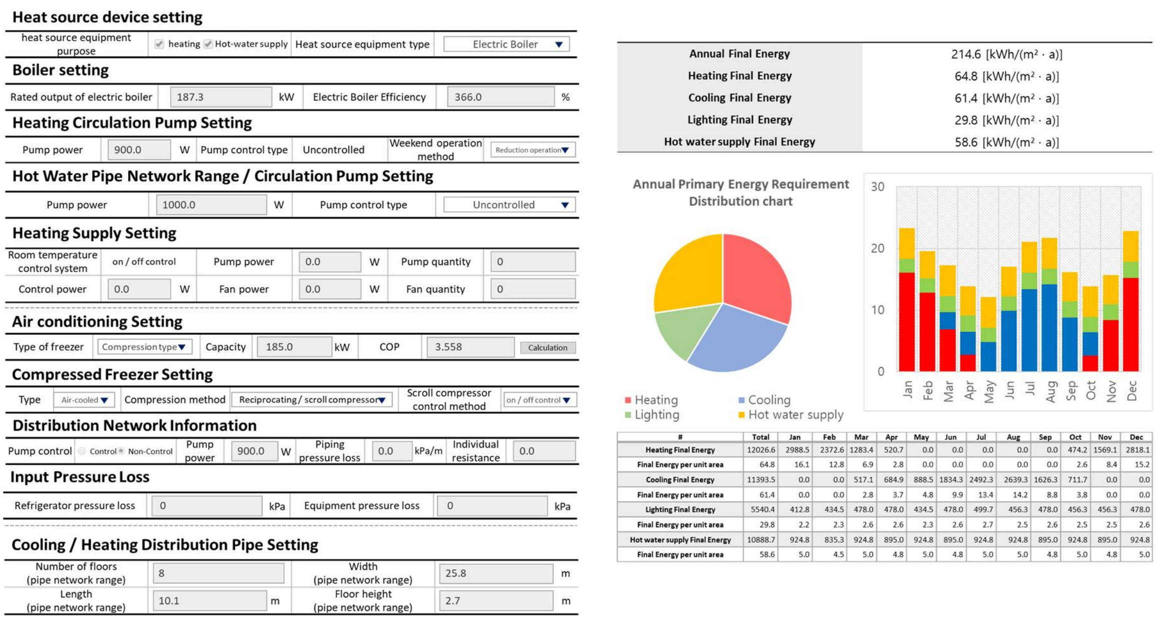
*3.3. Diagnosis and improvement of building energy performance*

For testbed 2, calculation of the DE was performed by inputting information, such as the insulation type of the target building, operation profile, indoor heating and cooling supply method, lighting degree, walls, and window areas (Figure 4.). In addition, the FE was analyzed by using the information of the heat source device (cooling / heating), heating and cooling distribution system, heating and cooling circulation device, distribution network scale and pressure loss, and hot water system application (Figure 5.).

Testbed 1 was diagnosed in the same manner, and calculations were performed to obtain the results of the diagnosis. The estimated PE calculated from the present state of the building, the state of the equipment, and the amount of usage information was 599 kWh / (m² · a) and 590.1 kWh / (m² · a) for each testbed, respectively. The energy efficiencies of non-residential buildings were determined to be six, which implied that energy efficiency improvement was urgent since that rating is low.


**(a)** Input architecture data of testbed2 **(b)** Demand energy

**Figure 4.** Building energy performance simulator UI: analysis of demand energy through diagnosis of the architecture part of testbed 2.




**(a)** Input facility data of testbed2 **(b)** Final energy

**Figure 5.** Building energy performance simulator UI: analysis of final energy through diagnosis of the facility part of testbed 2.

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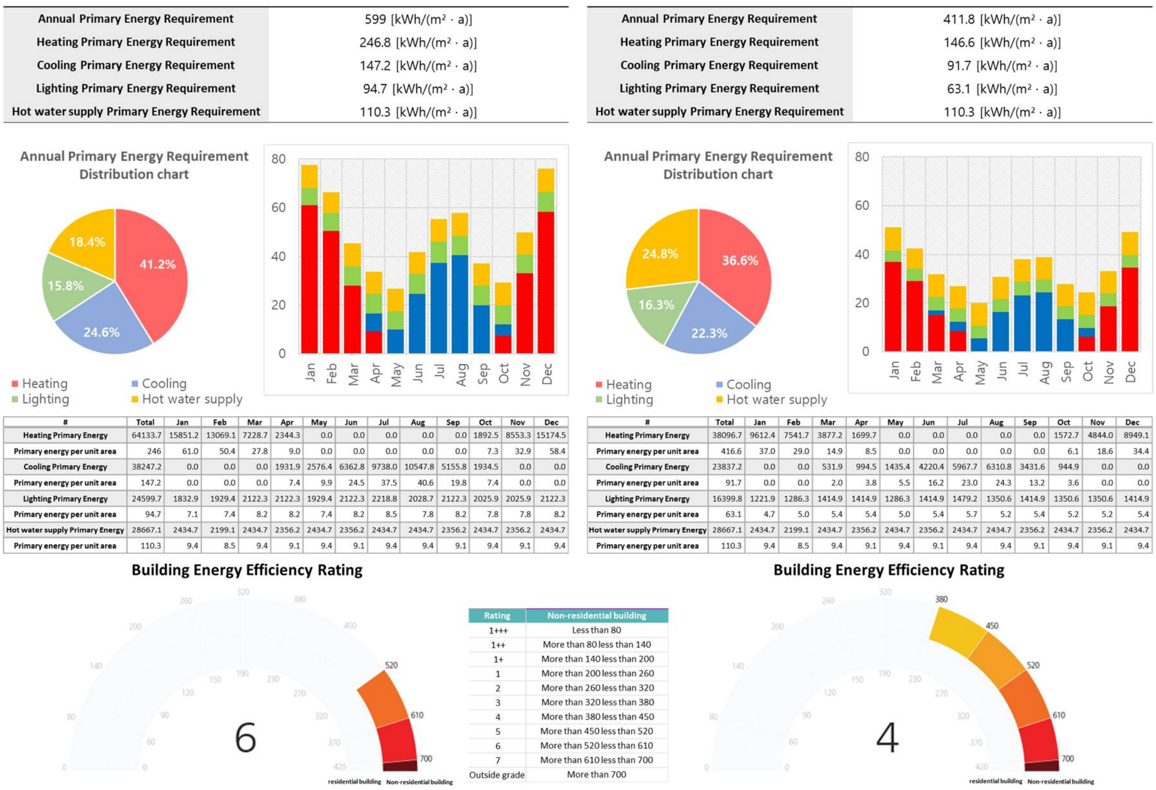
The annual primary energy for heating of testbed 1 was the highest at 41.2% (590.1 [kWh/(m² · a)]) among heating, cooling, lighting, and hot-water supply factors. Therefore, heating improvement was necessary. The DE after considering the facility change was analyzed and compared with the previous one. A comparison and analysis of the DE for the thermal percolation of the envelope (wall, roof, etc.) were conducted. The FE was calculated with the application of the heat flow rate according to the current energy saving design standard, and it was compared and analyzed. In addition, FE changes of the facility after its re-design were analyzed and compared with the pre-redesign FE. The amount of FE after the redesign was calculated with consideration of the type of the equipment to be replaced and its coefficient of performance (COP).

As shown in Table 4, the energy performance improvement plan was applied for testbed 1, and the analysis results are as follows. The primary energy requirement decreases from 599 kWh / (m² · a) to 411.8 kWh / (m² · a), resulting in a 32.3% reduction compared to existing buildings. In particular, the improvement of the heating facilities, which consumes the largest portion of energy, has a higher improvement percentage compared with the others (from 246 kWh / (m² · a) to 146.6 kWh / (m² · a)), which shows a significant reduction in the overall FE. As a result, the building energy efficiency rate also increases from six to four (Figure 6.).

**Table 4.** Energy performance improvement plan for test

| Field | Element | Input field | Changes |
|---|---|---|---|
| Building | Performance type | Shell heat conduction ratio | Applying current legal standards (01 → 17 years) |
| Equipment | Lighting equipment | Light density | When LED is applied (15W / m2 → 10W / m2) |
| | Heat source equipment | Efficiency (COP) | Energy consumption efficiency 1st grade product application |
| | Conveying equipment | Not applicable | Individual heating and cooling |
| | Heat recovery | Not applicable | Individual heating and cooling |




(a) Before improvement equipment (b) After improvement equipment

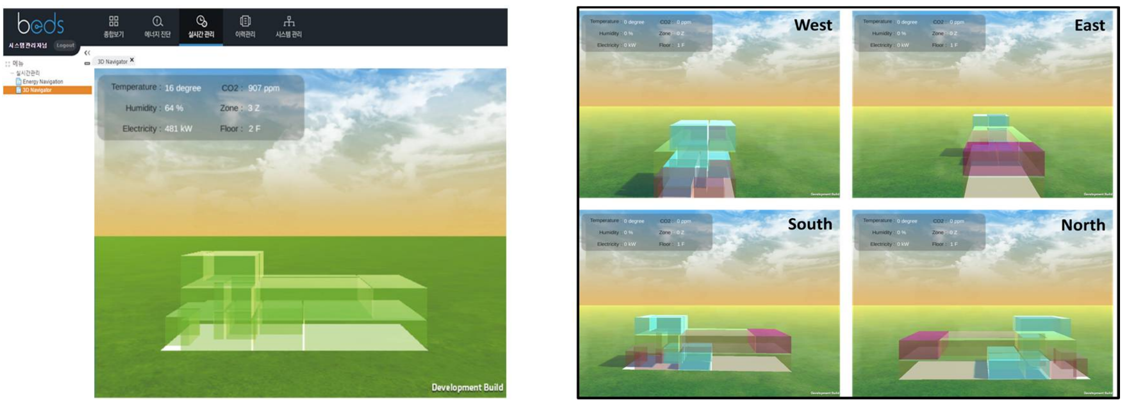
**Figure 6.** Estimated primary energy requirement and energy efficiency rate(testbed 1).

*3.4 Close-range photogrammetric-based 3D models and energy visualization*

We used a Canon COS 750D DSLR, a non-metric camera with a Canon EF-S 24mm F 2.8 STM lens. Close-up photographs were obtained at various angles of the testbeds, and a 3D model was constructed using a photomodeler developed in Canada's Eos system. To construct such a model, junction lines that can be recognized by the photomodeler are required to represent the same part of the building because the positions of these lines in different photographs obtained at different locations are different. In this study, we obtained photographs of the exterior of the building and photographed the contiguous sections of the exterior and interior spaces. The corners of the bottom and uppermost parts of the target building were hence considered as the junctions, and the lines connecting them were recognized as the building edges. Accordingly, a sufficient number of images were obtained to minimize modeling errors and eliminate modeling blind spots. In this study, a 3D model was constructed using CRP technology for testbed 2 (Figure 7.).


**Figure 7.** Building 3D modeling on testbed 2 using CRP

A building energy 3D visualization solution GUI for testbed 2, which visualized the energy consumption and environmental information of each zone of the building, was provided through the linkage between the model and built database (Fig. 8). To operate the 3D model effectively in the GUI, we implemented element functions, such as model objectification and an information presentation textbox. The model operation area enabled the visualization of the model with all its imbedded data at any angle or any specific zone. It was developed using Unity 3D, which is a 3D engine, and the information area was designed as a script in the engine to deliver the data of the selected zone. This solution can easily transmit the spatial information to users by implementing the building shape information as it currently exists. Moreover, it is possible to intuitively provide the energy usage characteristic of the specific zone to the user by assigning color differentiations according to energy consumption. In addition, we developed a GUI that can provide a 360° rotation function. Then, we uploaded the completed solution to the homepage. As mentioned previously, our goal was to enhance the intuitiveness of providing information to users via information visualization techniques.




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

**Figure 8.** Developed building energy 3D visualization solution

To improve the efficiency of energy feedback, we provided users with information on the webpage for a year to reduce energy consumption and encourage the building manager to upgrade the facility in accordance with our recommendations. The PE requirement measured in the preliminary building energy diagnosis was 590.1 kWh / (m² · a). However, based on the building energy that was re-diagnosed after the feedback in response to the visualization of the energy information for one year, the PE requirement was 424.4 kWh / (m² · a) (figure 9.). The energy saving rate was achieved, and the effect of visualizing and providing building energy information was found.


**(a)** Before apply visualization solution **(b)** Before apply visualization solution

**Figure 9.** Estimated primary energy requirement and energy efficiency rate before and after providing Energy visualization solution(testbed 2).

## 4. Conclusion

In this study, energy-saving measures were sought for buildings having a notable contributing role in climate change. Developed nations worldwide are reducing the proportion of fossil fuel use and increasing the proportion of renewable energy; however, older buildings remain less energy efficient. In addition, there are many buildings that require energy efficiency improvements on account of insufficient energy management regulations. Providing energy efficiency improvement scenarios of buildings using energy simulations is meaningful because it suggests directions for improvement for these inefficient buildings. Furthermore, it is predicted that data stored in a database in real time can provide diagnostic information to flexibly respond to changes in energy efficiency that occur from ongoing climate changes and deterioration of buildings..

To cope with climate change and energy problems, this paper presented a developed energy visualization solution for buildings with high-energy consumption. Two detailed key elements were applied in this study to the energy visualization solution: providing information and related recommendations for building efficiency improvements using energy simulations, and energy feedback based on those visualizations.

In addition, we developed a GUI to provide intuitive and clear feedback. This was accomplished by providing energy information in a 3D visualization method instead of in the existing textual and graph-oriented formats. We used the CRP method to construct 3D models and linked energy and

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environment information stored in real time in the database with the corresponding 3D model according to the given floor and zone. To enhance comprehension of the information inside the given building, we implemented a rotation function and elements that visualize the energy overuse points using color changes. The GUI was uploaded on the webpage and provided information to the user for one year.

As a result of the re-diagnosis of energy efficiency, we found that the visualization-based energy feedback led to possible changes in user behaviors and increased the energy-efficiency rating compared to giving feedback via the current format of monthly bills.

Visualization energy feedback enhances user motivation to more effectively manage energy consumption. However, users do not know what information they should focus on and the factors that contribute to energy savings. Identifying high-interest energy information for the user can increase the energy management efficiency. Therefore, in future research, we will conduct an assessment on residents and energy management experts to analyze usage patterns based on the user experience research method (UXRM) and thereby elucidate the user degree of interest and level of concentration on the given information.

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**Author Contributions:** Tae-Keun Oh and Seunghee Park propose the main idea of the paper. 3D modeling using CPR method is constructed by Donghwan Lee. Energy visualization solution is developed by Donghwan Lee, Minsoo Park and Gichun Cha. The paper is written by Minsoo Park and is revised by Donghwan Lee.

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

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