Research on inefficiency analysis method of building energy utilizing time series data

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Abstract. Purpose; Our research purpose is to utilize time series data related to building energy and perform an inefficiency analysis of building energy efficiency. Development; We developed a cloud building energy and environment monitoring system (cloud Building Management System (BEMS)) and an optimized control system (an artificial intelligence [AI] control system). Methodology; First, we designed an inefficiency analysis model and the analysis steps. Next, this model was tested in several actual buildings, and the method was confirmed to be adaptable. Finally, through iterative adaptations based on the results, we significantly improved our method. Findings; (1) The developed cloud BEMS and AI control system were confirmed to be useful for a) improvement of building management, b) improvement of equipment and system, and c) renovation. (2) Our analytical method and its steps can quantify inefficiency. (3) When using this methodology, we can quantitatively predict before implementation the effect of a) building improvement, b) equipment and system improvement, and c) renovation. Originality/value; Cloud BEMS collects time series data related to building energy consumption from sensors and building automation systems and accumulates data in a cloud server. The AI control system and analytical method finds energy inefficiencies and improves the operation of the building. Moreover, this improvement in operation is unmanned and carried out automatically. Keywords; Sustainable, Internet of things (IoT), machine learning, artificial intelligence (AI), energy management system (EMS), energy conservation, environment efficiency, optimized control, CO₂ reduction.

Paper type; Academic paper.

1. Introduction-technical and social background
Dependence on the growth of thermal power generation triggered by the Great East Japan Earthquake
The dependence on fossil fuels from overseas, which was approximately 75% in the 1970s, was down to approximately 60% just prior to the Great East Japan Earthquake in 2010, but it had risen to approximately 80% by 2015.¹

Increased power generation costs
After the Great East Japan Earthquake, due to the long-term suspension of nuclear power generation, the amount of electricity generated by thermal power generation increased significantly. Due to the dramatic increase in thermal power generation, additional fuel costs of approximately JPY 15.5 trillion (USD 141 trillion) have been generated over the six years from fiscal year (FY) 2011 to FY 2016. In 2016, additional fuel costs of approximately JPY 1.3 trillion (USD 11.8 trillion) were paid to resource countries; a further cost of approximately JPY 40,000 per year for each family of four (USD 365 per year) was also incurred.¹

Change in greenhouse gas emissions in Japan
Greenhouse gas emissions since the Great East Japan Earthquake have increased. Emissions in FY 2012 increased by 0.87 billion tons from the FY 2010 level. Although there was a slight decrease in emissions
from sources other than electricity, electricity increased by 112 million tons compared with FY 2010 due to increased thermal power generation for nuclear power plant substitution.[2]

Status of energy management in small and medium-sized buildings
Most buildings and building owners have neither energy control staff nor an energy manager (an adviser for energy conservation in the building). (see Table 1). Most small and medium-sized buildings do not install building automation (BA) and building energy management systems (BEMS). However, the importance of BEMS has been recognized, and the market is predicted to grow to JPY 1.553 trillion by 2020. This is 70.8% greater than the size of the market in 2013.[3]

2. Research questions and purpose regarding design and the developed system
Our research covered small and medium-sized buildings. In addition to buildings and facilities that were not equipped with BA and BEMS, buildings with insufficient function and sensors for optimization were also targeted, even in large buildings (see Table 2). The research targeted common buildings with the largest market scale that implement energy conservation at normal levels. Regarding no human resources, in small and medium-sized buildings, it was found that facility managers and energy managers were often absent. Therefore, it was necessary to confirm the energy related information of the building remotely.

| Building type and floor area ㎡ | Facility manager | Energy controller | Building automation (BA) | Building energy management system (BEMS) |
|-------------------------------|------------------|-------------------|--------------------------|----------------------------------------|
| Commercial buildings          |                  |                   |                          |                                        |
| Small-scale Under 300 ㎡      | Absent           | Absent            | No installation          | No installation                        |
| Middle-scale 300~3,000 ㎡     | Absent           | Absent            | No installation          | No installation                        |
| Middle-scale 3,000~8,000 ㎡   | Absent           | Absent            | Depends on circumstances | Depends on circumstances                |
| Large-scale 8,000+㎡          | Absent           | Depends on circumstances | Installation | Depends on circumstances               |
| Office buildings              |                  |                   |                          |                                        |
| Small-scale Under 300 ㎡      | Absent           | Absent            | No installation          | No installation                        |
| Middle-scale 300~3,000 ㎡     | Absent           | Absent            | No installation          | No installation                        |
| Middle-scale 3,000~8,000 ㎡   | Absent Administrator only | Absent            | Depends on circumstances | Depends on circumstances                |
| Large-scale 8,000+㎡          | Absent Administrator only | Absent            | Depends on circumstances | Depends on circumstances                |
| Hotel buildings               |                  |                   |                          |                                        |
| Middle-scale 3,000+㎡         | Absent           | Absent            | No installation          | No installation                        |
| Large-scale 8,000+㎡          | Absent Administrator only | Absent            | Depends on circumstances | Depends on circumstances                |

Note: From our research—a total 40 buildings.
Regarding the building function conditions, in many cases, BA is not introduced in small to medium-scale buildings, and energy and environment-related sensors are not installed. Our research asks whether sustainable technologies are applicable to small buildings with high energy consumption, inefficiency, and energy loss. It aims to develop a cloud building energy and environment monitoring system (cloud BEMS) that achieves high economic performance and high efficiency energy use for various building locations.

The cloud BEMS has been developed and built during a nine-year research collaboration between various companies related to technology and business and the Institute of Industrial Science, the University of Tokyo. All buildings targeted for this research have already been built and are operating without a facility manager or energy manager.

2.1 Research purpose
The other purpose of our research is to utilize time series data related to building energy and perform an inefficiency analysis of building energy efficiency.

2.2 Flow of system introduction and effect confirmation (operation improvement)
The flow from system introduction to effect verification is shown in Fig. 1.

Fig. 1 The flow from system introduction to effect verification.
In the preliminary survey, we obtained information related to the energy of the target building. Next, in the field survey, we interviewed or visually checked the content of the initial survey and the actual building situation, and we made inquiries regarding information that was not included in the preliminary survey documents, such as operation status and failure location. Then, in the data collection phase, we confirmed energy usage and related items and the measurement control items necessary for optimum control, and these data were stored on a cloud server. We utilized time series data to reveal operational inefficiencies. Based on the results, we will implement optimal control of operation.

2.3 Relationship between data users and data
We show relationship diagrams concerning stakeholders that utilize data and data utilization acquired from buildings (see Fig 2). Small and medium-sized buildings must deliver building information to stakeholders because there is no manager. Showing each stakeholder the result of the analysis of data accumulated on the cloud server is an effective means of creating subsequent energy conservation. The information required by each stakeholder is different and depends on individual circumstances, such as management costs, CO2 emissions, energy saving fees, and cost savings. The items of interest for the tenant user are different from those of the administrator. Generally, in office buildings, administrators are not interested in energy usage and are interested in the comfort of thermal environment.

2.4 Research points and solution policies
The target small office buildings, hotels and commercial buildings are without energy managers and energy efficiency is often inferior to those with managers. As a result of The main research is whether it is possible to grasp analysis results well if the energy can be remotely visualized by introducing the developed Cloud BEMS.
3. Framework of developed system

This section gives an overview of the developed design module. Each module devised an interface so that it can function separately (see Fig 3). In the upper part of the figure, local refers to the target building or facility. The following local shows the user side. The cloud in the figure is a service that accumulates big data through the Internet.

Measurement system module:
This function module includes ① Building items with related to energy use, ② Sensors, ③ Measurement devices, and ④ Data transfer section, which uses an open protocol and translates the data into a generic protocol on TCP/IP.

Storage system module:
This function module includes ⑤ Receiver and real-time data collection section, and there are data servers and data tables for each project.

Display system module:
This function module includes ⑥ Data display section, which has a web server function.

Visualization system module:
This function module includes ⑦ Data visualization section and ⑧ Users. The visual section is a web browser on a personal computer and some smart devices connected through the Internet. Users check the results from graphs and data. Users can also enter relevant data.

Devise control system module:
This function module includes ⑪ Control section and ⑫ Equipment. The control section has a special protocol that can adopt many kinds of mechanical and electrical (M&E) equipment and systems.

Analysis system module:
This function module includes ⑨ Local data analysis section ⑩ Central data analysis sections that calculate and compare the energy consumption of the best results both past and current. The local data analysis section includes target value and indicators for energy consumption and efficiency, and the central data analysis section includes value and indicators for energy consumption and efficiency.

Fig 3 Framework of developed system.
4. Case study using time series data

4.1 Energy conservation effect of using a visualization system in an existing 24-hour store

The visualization system gives us real-time information about energy use, outdoor and indoor temperature and humidity, operation conditions regarding M&E equipment, and the state of the system.

When the visualization system was installed in an existing general store, we were able to make a ▲ 3–5% reduction in total energy use. All staff members controlled the indoor temperature setting. Cleaning the filters in the air conditioning system reduced air conditioning energy consumption by approximately ▲ 9.2% (see Graph 1). Controlling the indoor and equipment lighting illuminance was found to reduce the energy use of lighting by ▲ 42% (approximately ▲ 17 kWh/day use). The results of controlling daylight and lighting demonstrated that the visualization system is an important technology for energy conservation.[4]

4.1.1 The energy conservation effect of using the visualization and optimized control systems in an existing 24-hour store

To evaluate the energy conservation effect of using the visualization system and the optimized control system (an artificial intelligence [AI] control system), we installed them in the M&E equipment and systems of an existing store.

The targets were interior and exterior lighting, Heating, Ventilation, and Air Conditioning (HVAC), air conditioning temperature settings, refrigerator temperatures, and demand control of electric power. The optimized control of the M&E systems in the existing building reduced total energy use by approximately 10.3%. Controlling solar radiation and natural ventilation further reduced total energy use by approximately ▲ 14%. This process included the analysis of information from sensing data and feedback control.

4.1.2 Sustainable store effect

Location, circumstance, district, site area, and aspect for architecture are very important for energy conservation and energy creation. Our research and development and the design model increased efficiency, reducing total energy use by ▲ 30–70%. None of the small commercial stores or small 24-hour stores in our study have on-site maintenance staff. The developed design model and AI control system addresses this issue. Table 3 shows the conditions of the target stores and the results of introducing the system. Although the size of the store is about the same size, the direction of the area and the store are different. Also, the energy saving system adopted is different, so the energy saving effect is different.
| Giving conditions of each site | Items | Architectural and Energy conservation and Energy creation technologies of building services | Energy conservation rate 2010 ratio | User’s actions for energy conservation | Sustainable store |
|--------------------------------|-------|---------------------------------------------------------------------------------|-------------------------------|-------------------------------------|-------------------|
| Climate area code for energy district conservation | At all district | All (6) Light (6) | 294 (2019) 913 012052 | Void | Void |
| Store building type | Independent type | ○ ○ ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ | ○ ○ ○ ○ |
| The surrounding circumstances | Relationship of the neighborhood | North neighborhood | East-West Open | No neighborhood | Sustainable store |
| Business hours | 24 hours per day (65 days) | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ | ○ ○ ○ ○ |
| Energy classification | Electricity (gas and others) | Water | Electrical energy | Electricity | Electricity | Electricity | Electricity | Electricity | Electricity |
| Architectural and Energy conservation and Energy creation technologies of building services | Lighting system | Standard type | Standard type | Standard type | Standard type | Natural ventilation | Standard type | Standard type | Standard type |
| Energy conservation and Energy creation | Other Natural energy | Standard type | Standard type | Standard type | Standard type | Gravity ventilation | Standard type | Standard type | Standard type |
| Special equipment for small 24 hours convenience store | Water spray for compressor | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ | ○ ○ ○ ○ |
| Energy conservation for operation | Water source heating | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ | ○ ○ ○ ○ |
| Energy reaction equipment and system | Solar panel | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ | ○ ○ ○ ○ |
| Energy conservation and creation | Bioreactor | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ | ○ ○ ○ ○ |
| Energy conservation and Energy creation | Water cooling system | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ | ○ ○ ○ ○ |
| User’s actions for energy conservation | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ ○ ○ | ○ ○ ○ ○ | ○ ○ ○ ○ | ○ ○ ○ ○ |

Table 3. Comparison of the energy conservation and creation effects related to sustainable technologies. [4]
4.2 Case study utilizing outside air for refrigerator in winter in an existing 24-hour store

In small commercial stores, energy consumption related to refrigerated air reaches 40 to 50% of the annual usage. In one case study, outside air was sent to the refrigerator during the winter. This system can cool food without using a compressor. We analyzed the time series data and verified the energy saving effect.

In addition, this case is the measurement result by the cold district project (see Graph 2). During a six month period from November 2013 to April 2014, a total of 2,312 hours of outside air cooling was possible (see Graph 3).

![Graph 2](image1)

**Graph 2.** Comparison of the amount of electricity used with and without outside air cooling (November 1, 2013–April 30, 2014).

![Graph 3](image2)

**Graph 3.** Outside air cooling control time (hr) (November 1, 2013–April 30, 2014).

4.3 Case study of 120 office buildings to analyze the relationship between outside air temperature and power demand

We analyzed the relationship between the daily power consumption per unit area of 120 buildings and the peak power per unit area with respect to the correlation between electricity consumption per day and the peak power. Data aggregation was carried out by classifying the difference between contract power in 2009 and peak power in 2010, and buildings with contract electric power of 500 kW or more and buildings with contract power less than 500 kW (see Graphs 4 and 5).
There was no significant correlation between contract power in 2009 and electric power consumption per day, and peak electric power tended to be large with respect to daily electricity consumption. However, in 2010, when countermeasures were taken to suppress peak power demand, a strong correlation was found between power consumption and daily peak power demand, regardless of the size of the building. As a result of peak power suppression for each building, it appears that there is a correlation between power consumption and peak power. In particular, when the cooling load is low, the correlation with the outside air is low.

Graph 4. Correlation between contract power and summer peak power and day maximum power in summer 2010 (contract power 500 kW over, 37 buildings).

Graph 5. Correlation between contract power and summer peak power and day maximum power in summer 2010 (contract power 500 kW under, 83 buildings)
4.4 Case study of large-scale complex buildings

In a case study of a large exhibition hall, we optimally controlled the air conditioning of the exhibition hall and reduced district heating and cooling (DHC) cold water demand by 6.5%. (see Figure 4)

Correlation analysis between outside air temperature and cooling demand shows that there is cooling demand when cooling is unnecessary.

Also, it was found that there was a loss in the cold water conveying power because the cooling pump capacity was excessive (see Graph 6).

Cooling load and frequency of occurrence were counted. The maximum cold water load is 45,000 MJ, which shows that the 50,000 MJ equipment capacity is unnecessary. The frequency of occurrence of small cold water loads (5,000 MJ) accounts for 71% of the total; 5,000 MJ is approximately 10% of the peak cold water demand value. In other words, because it takes a long time to drive with a very small capacity, it is necessary to review the system (see Graph 7).
5. The outcome of this research and development
The cloud BEMS and the AI control system that we developed were able to optimize operation while simultaneously accumulating energy related data in the cloud server. We found that these systems were useful for predicting the maximum demand and for discovering inefficiencies in equipment and systems. The energy usage of the small and medium-sized building group can be automatically optimized remotely. Furthermore, this can be applied to large scale complex buildings.

6. Conclusion
The developed the cloud BEMS and AI control system were confirmed to be useful for improving building management and improving equipment and system renovation. Our analytical method and its steps can quantify inefficiency and loss regarding building energy. Prior to implementation, when using this methodology, we can quantitatively predict the effect of 1) building improvement, 2) equipment and system improvement, and 3) renovation.

7. Future issues
In research results, energy efficiency can be improved by improving the operation of small to large-scale buildings and facilities, and it is considered that energy waste can be eliminated by solving the following problems in the future.

(1) Increasing the number of relevant sensors.
(2) Simplification and diffusion of systems.
(3) Develop services as a social infrastructure.
(4) Quantification of reduction effect in a wide range by building types and facility systems.
(5) Expanding the scope of application of AI and machine learning.

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