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

Magori Bumpei, Lecturer, Institute Industrial Science, the University of Tokyo, Ph.D. (Engineering)
magori@iis.u-tokyo.ac.jp

Tomonari Yashiro, Professor, Institute Industrial Science, the University of Tokyo, Ph.D. (Engineering)

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, CO_2 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]

Table 1. No facility manager and no energy control staff at the building site.

Items	contents	note
Building type	Commercial / Office Building / hotel / University	
Building scale	Main Small / middle / Large-scale buildings with insufficient function	
Human resource conditions	Facility manager absent	
	Energy manager absent	
	Building administrator absent	
	Building management stuff absent	
Building function conditions	BA has not been introduced.	Add monitoring control device
	No interface with BA	Add interface
	No electric energy sensor	Add necessary sensor
	No indoor temp sensor	Add necessary sensor
	No interface with M&E devices	
Other conditions	No serious breakdown of equipment.	
	The equipment life has not passed. Moreover, it has not done serious deterioration	

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.

Table 2. Target buildings of our research.

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 8000+㎡	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 8000+㎡	Absent Administrator only	Absent Administrator only	Depends on circumstances	Depends on circumstances
Hotel buildings	Middle-scale ~3,000 ㎡	Absent	Absent	No installation	No installation
	Middle-scale 3,000~8,000 ㎡	Absent Administrator only	Absent	No installation	No installation
	Large-scale 8000+㎡	Absent Administrator only	Depends on circumstances	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.

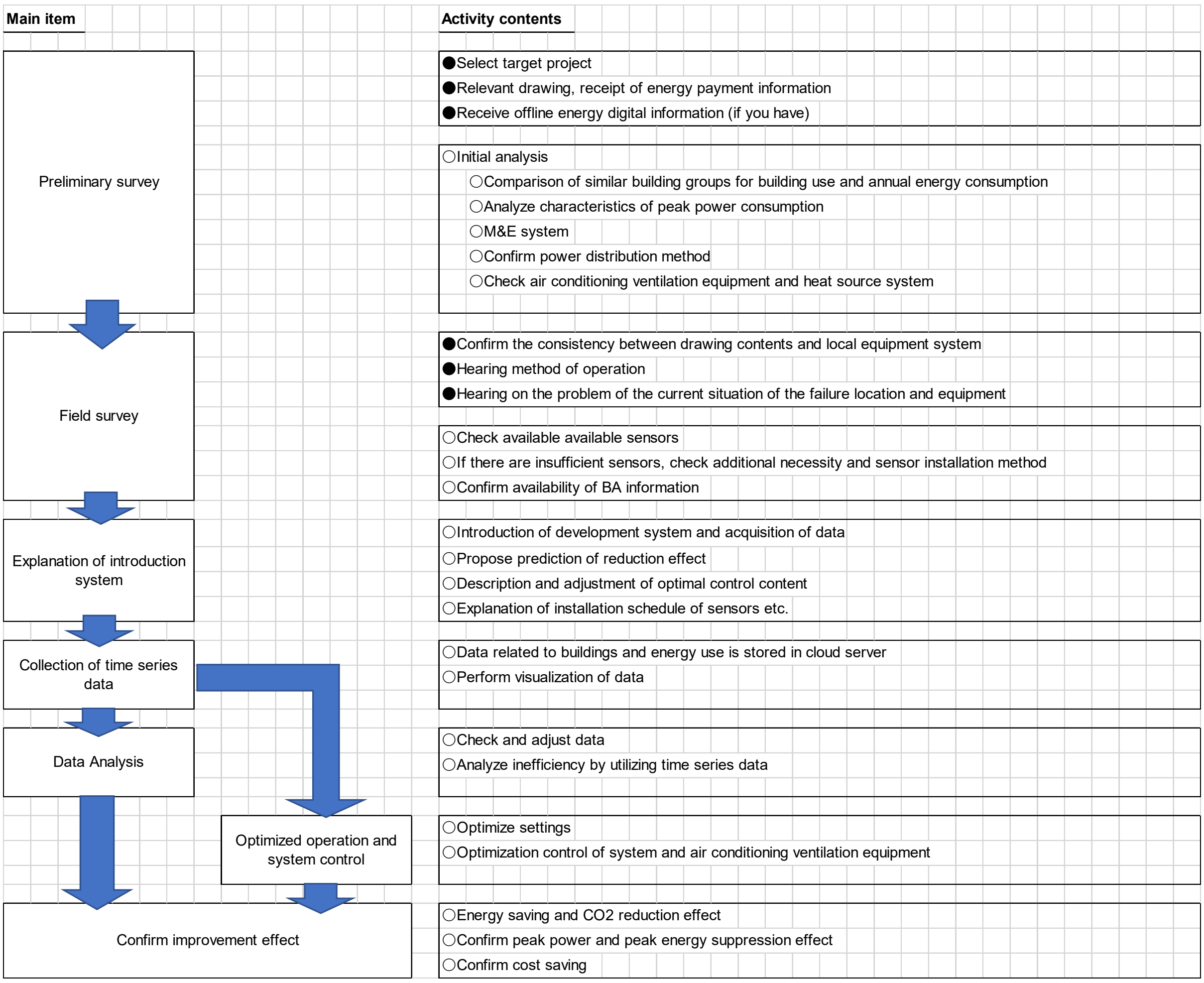


Fig. 1 The flow from system introduction to effect verification.

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, C02 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.

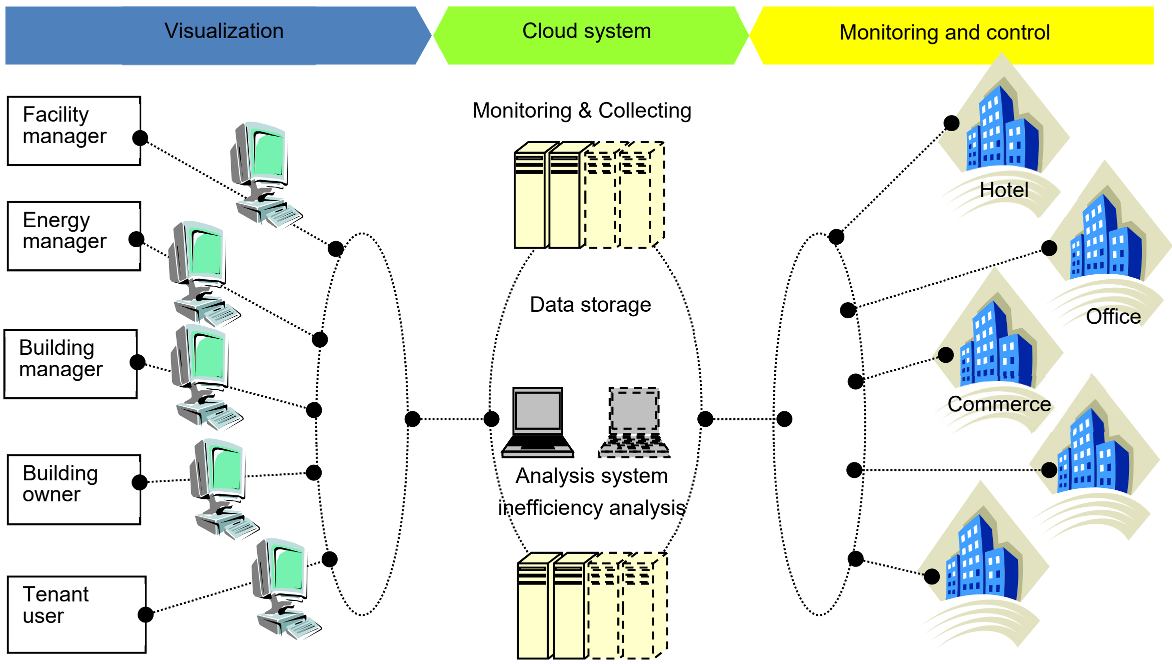


Fig 2 Relationship between data users and data.

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.

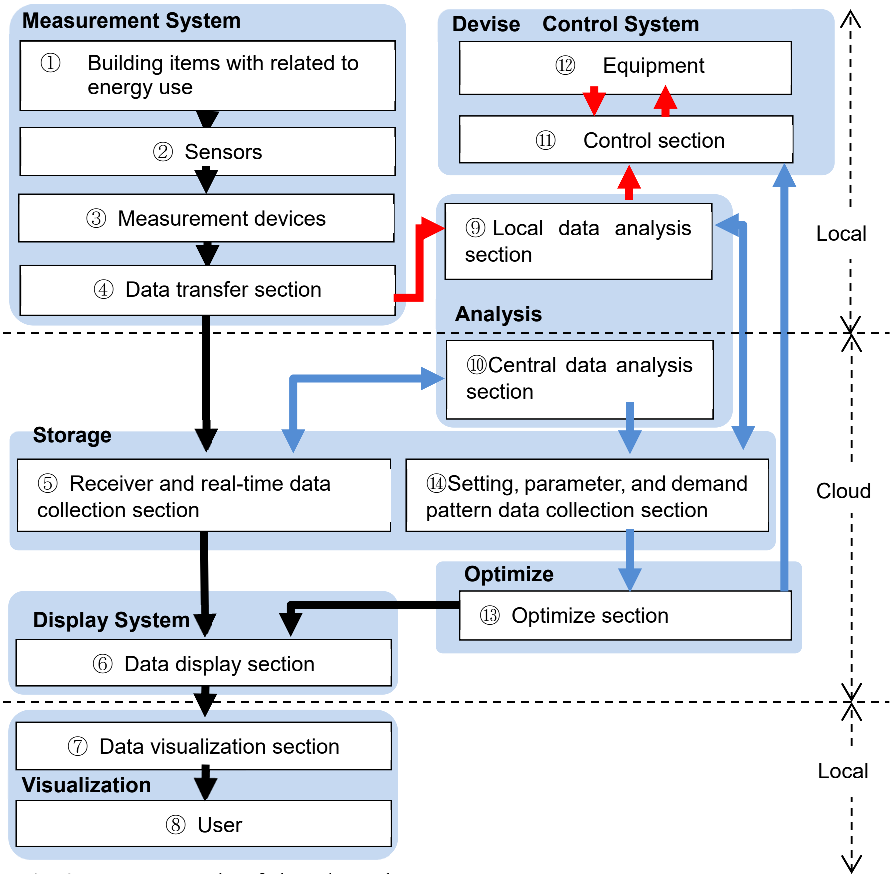


Fig 3 Framework of developed system.

Measurement system module:
This function module includes ① Building related items 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, 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.

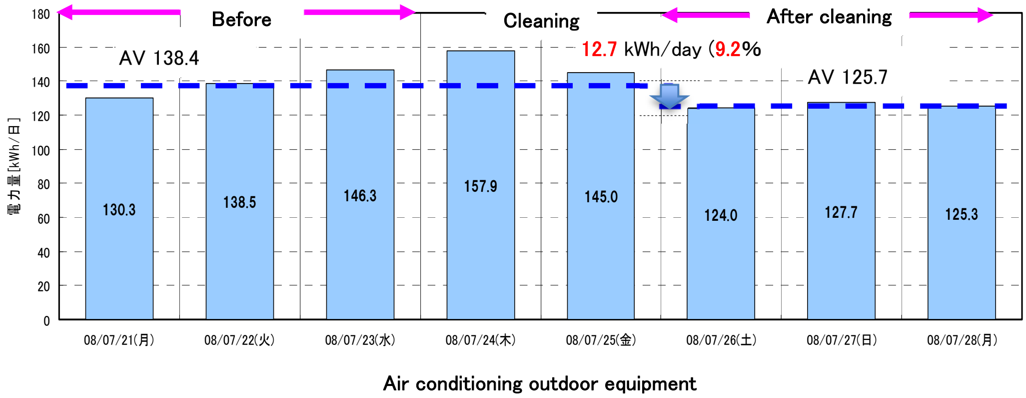
IOP Conf. Series: Earth and Environmental Science **294** (2019) 012052 doi:10.1088/1755-1315/294/1/012052

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]



Graph 1. Comparison of the electricity used by air conditioning systems before and after filter cleaning (July 21–28, 2008).

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.

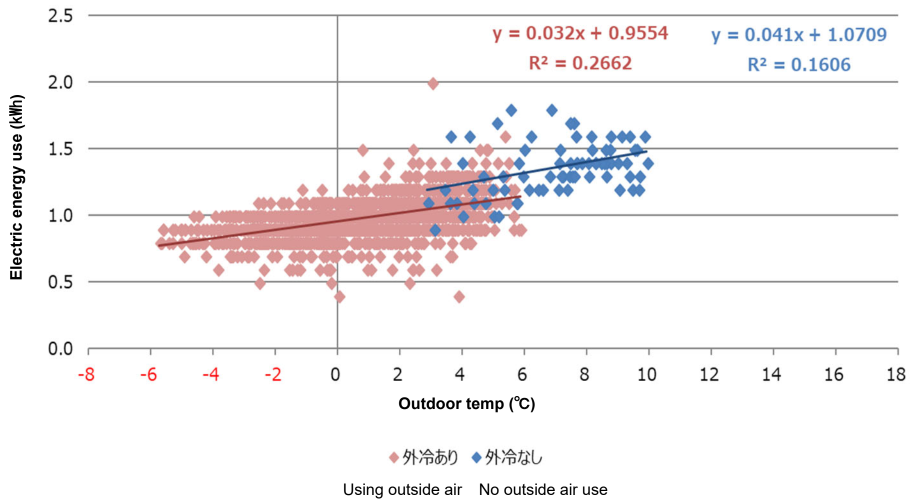
IOP Conf. Series: Earth and Environmental Science **294** (2019) 012052 doi:10.1088/1755-1315/294/1/012052

						○:adaptation		－: No relation			
			Items	general existing store with visualization system			general existing store with visualization and AI control	Sustainable srore			
				HO	MI	TA	MI	EB	UR	TO	UM
Giving conditions of each site	Climate area code for energy conservation	I-VI areas code (Old codes)、Cold and hot district 1～8 areas code (New codes)	All district	Ⅳ(6)	Ⅳ(6)	Ⅳ(6)	Ⅳ(6)	Ⅳ(6)	Ⅱ(2)	Ⅳ(6)	Ⅳ(6)
	Store building type	Tenant type	○	－	－	－	－	－	－	－	－
		Independent type	○	○	○	○	○	○	○	○	○
	Direction	Front direction	All direction	North	West	South west	West	East	East	North	South
	The surrounding circumstances	Relationship of the neighborhood	－	North neighborhood buiding, east wall	West neighborhoo dEast-West Open	South-East neighborhood Others open	West neighborhood East open	Eest neighborhood East open	No neighborhood	South and West wall	No neighborhood
	The store area	The total floor area (the air conditioning area), the parking area ㎡	from 100 to 200	121(93)	175(104)	153(111)	175(104)	200(140)	200(140)	200(140)	200(140)
	Business hours	24 hours per 365 days	○	○	○	○	○	○	○	○	○
	energy classification	Electricity (gas and others)	Electricity water	Electricity water	Electricity water	Electricity water	Electricity water	Electricity water	Electricity water	Electricity water	Electricity water recycle oil
Energy conservation and Energy creation	Archtectural sustainable technologies of building	Insulation (envelope)	Standard type	Standard type	Standard type	Standard type	Standard type	High spec insulation	High spec insulation	High spec insulation	High spec insulation
		Solar radiation control (canopy)	Standard type	Standard type	Standard type	Standard type	Standard type	Thermal barrier Thermal insulation	Thermal barrier Thermal insulation	Thermal barrier Thermal insulation	Thermal barrier Thermal insulation
		Solar radiation control (window)	Standard type	Standard type	Standard type	Standard type	Standard type	Insulation Sunlight Shsding	Insulation Sunlight Shsding	Insulation Sunlight Shsding	Insulation Sunlight Shsding
		Daylight utilization	－	－	－	－	－	Indirect sunlighting	－	－	－
		Natural ventilation	－	－	－	－	－	Natural Ventilation	－	Natural Ventilation	－
	Energy conservation technologies of building services	High-efficiency heating and cooling equipment system	Standard type	Standard type	Standard type	Standard type	AI control	Celling radiation Well HP AI control	Well HP AI control	Wall radiation Heat pipe AI control	Celling radiation Air HP AI control
		Lighting system	Standard type	Standard type	Standard type	Standard type	Lighting control	LED Lighting control	LED Lighting control	LED Lighting control	LED Lighting control
		Ventilation system	Standard type	Standard type	Standard type	Standard type	Standard type	Natural Ventilation	Standard type	Standard type	Standard type
		Greening (watering)	－	－	－	－	－	－	－	Greening Splay	－
		Geothermal heating and cooling	－	－	－	－	－	Well	Well	Geothermal heat pipe	－
		Groundwater use watering	－	－	－	－	－	Water splay	Snow water	－	－
		Optimized control	－	－	－	－	Lighting Air condition	radiation panel system Heat pump	FCU, Snow strage system	radiation panel system Heat pump	radiation panel system Heat pump
	Energy creation equipment and system	PV system	Installed	Installed	Installed	－	－	Installed	Installed	Installed	Installed
		Solar panel	－	－	－	－	－	－	Floor heating	－	－
		Biomass power generation	－	－	－	－	－	－	－	－	Biomass generation
		Snow utilization	－	－	－	－	－	－	Snow air conditon system	－	－
		Other Natural energy	－	－	－	－	－	－	－	Gravity ventilation	－
	Special equipment for small 24 hours convenience store	High-efficiency refrigerator	Standard type	Standard type	Standard type	Standard type	AI control	－	－	－	－
		Separate style compressor	－	－	－	－	Installed	Installed	Installed	Installed	Installed
		Refrigerator with a door	－	－	－	－	－	－	－	－	Installed
		Water spray for compressor	－	－	－	－	－	Well water splay system	－	－	－
	Energy conservation for operation	Visualization system	－	Energy, indoor and outdoor temp humidity	Energy, indoor and outdoor temp humidity	Energy, indoor and outdoor temp humidity	Energy, indoor and outdoor temp humidity	Energy, indoor and outdoor temp humidity	Energy, indoor and outdoor temp humidity	Energy, indoor and outdoor temp humidity	Energy, indoor and outdoor temp humidity
		Evaluate, improvement and optimize for operation conditions	non	Installed	Installed	Installed	Installed	Installed	Installed	Installed	Installed
		Optimized cleaning and maintenance	Standard manual	Standard manual	Standard manual	Standard manual	condition monitering	Standard manual	Standard manual	Standard manual	Standard manual
	User's actions	User actions for energy conservation	－	－	－	－	－	－	－	－	－
Energy conservation rate 2010 ratio			2010 average	▲3～5%			▲10～14%	about ▲30%	about ▲50%	about ▲60%	about ▲70%

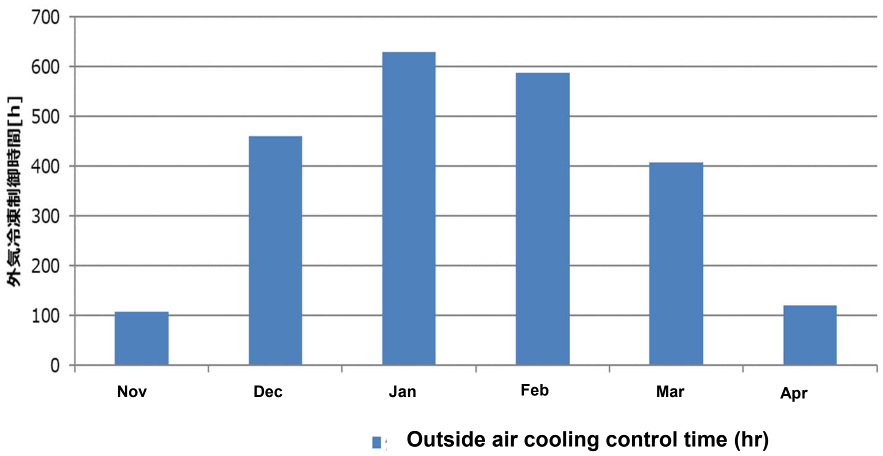
Table 3. Comparison of the energy conservation and creation effects related to sustainable technologies. [4]

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).

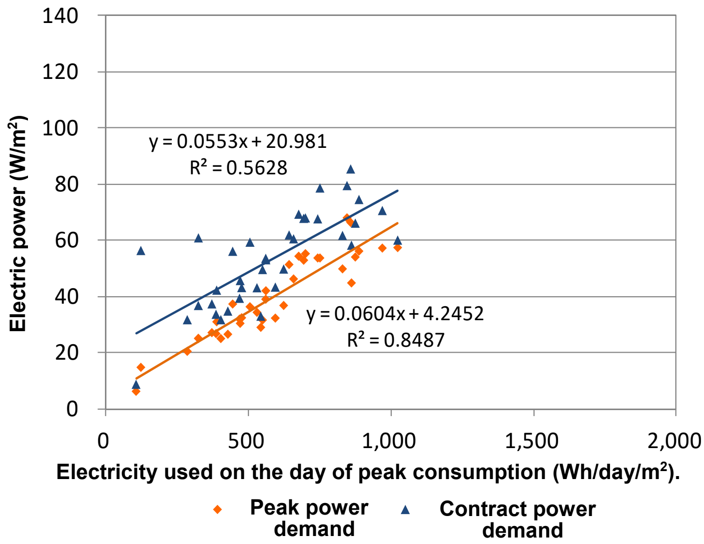


Graph 2. Comparison of the amount of electricity used with and without outside air cooling (November 1, 2013–April 30, 2014).

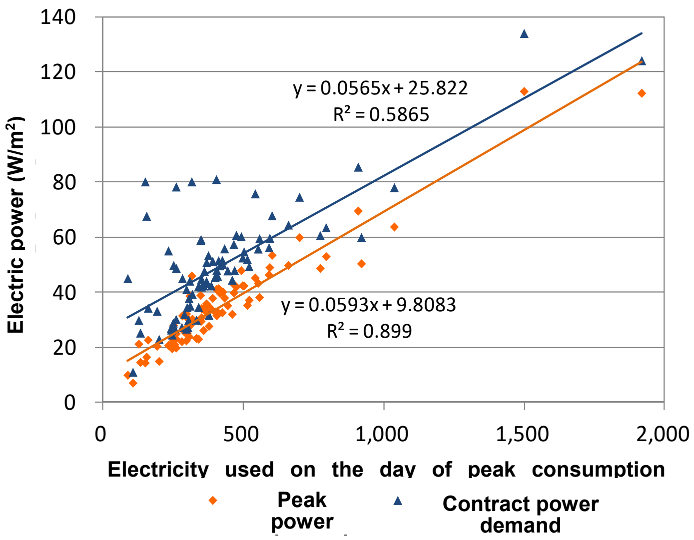


Graph 3. Outside air-cooling control time (hr) (November 1, 2013–April 30, 2014).

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 (se Graphs 4 and 5).



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)

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.

IOP Conf. Series: Earth and Environmental Science **294** (2019) 012052 doi:10.1088/1755-1315/294/1/012052

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)

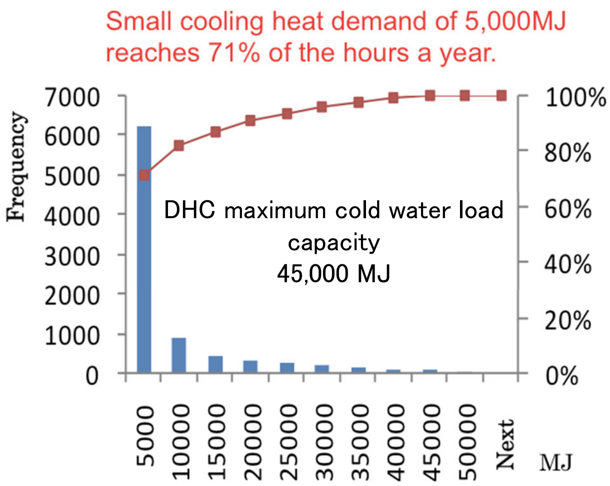
Figure 4. Pacifico Yokohama external view.

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).

Graph 6. Pump capacity (MJ) and outdoor temp (℃).

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).



Graph 7. Frequency of occurrence of cold water load.

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.

Acknowledgements

This research was able to introduce the developed system to buildings of various uses through the cooperation and support of the Academic–industry Partnership for Proactive & Holistic Energy Demand Management for the Construction Sector, Social Cooperation Program (2012–2016); the Machine Learning and AI Control Technology for Energy Conservation and Creation in the Construction Sector; and cooperative researchers (2017–) at the Institute of Industrial Science, the University of Tokyo. As a result, we acquired big data related to various buildings and analyzed energy inefficiency. We deeply appreciate the teachers and the people concerned who gave us instruction.

IOP Conf. Series: Earth and Environmental Science **294** (2019) 012052 doi:10.1088/1755-1315/294/1/012052

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