A study toward the realization of net zero energy building in urban areas

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Abstract. In this paper, we report the results of an empirical study on an urban ZEB pilot building constructed in May 2014. The objectives of the research are to develop individual elemental technologies for ZEB and to demonstrate the energy of the entire building. In order to realize and popularize urban ZEB, we have developed and demonstrated a facade design that makes maximum use of the outer walls of buildings, a lighting system that utilizes a skeleton ceiling made of reverse beams, and a core radiation heating and cooling system. As a result of the demonstration while actually operating it as an office building, PEB was achieved with an annual energy balance of 43 [MJ/m²a], energy consumption: 437 [MJ/m²a], energy generation: 480 [MJ/m²a]. In addition, we will report the results of the demonstration on the characteristics such as peak power of buildings obtained through the operation and future problems such as reduction of standby power. As a result of this demonstration, it was possible to extract elemental technology necessary for realization of ZEB in urban areas, building scale, future problems, etc.

1. Introduction
In recent years, many best practices of Zero Energy Building (ZEB) have been reported in Europe, the United States and Asian countries. Also, Japan is also making full effort of ZEB activities. [1] The target of this research is to ZEB office buildings in urban areas, and verify their possibilities and extract problems through demonstration in a real building. To realize ZEB and PEB (Positive Energy Building) in buildings with limited sites, policy and technical problems for ZEB realization will be arranged through fundamental requirements such as building size and performance verification of elemental technologies.

2. Toward realization of Urban ZEB (ZEB targeting office buildings in urban areas)
This is the first project of the Urban ZEB. It aims to realize and popularize ZEB, which are becoming a global trend. (Photo 1) Broadly speaking, this project has two purposes. The first is that the building itself must achieve an annual primary energy balance of 0 (zero) to demonstrate the Urban ZEB prototype. The second is to always incorporate ultimate energy-saving technologies and cutting-edge power generation technologies, which are predicted to evolve rapidly, as well as to verify their impact, in addition to further reducing costs and improving workability for universal technologies.

2.1. Basic concept
In considering a ZEB for office buildings in urban areas, we noted themes in the area of facilities, namely (1) to promote the coexistence of ultimate energy savings and intellectual productivity by combining a thorough reduction in load through automation and high efficiency with the personal satisfaction enabled by the individual adjustment function (self-select). In addition, in urban areas, where sites are subject to...
many restrictions, (2) appropriate plans for power generation equipment and optimization of their effects are required; we think these are the keys to popularizing ZEB. (Figure 1)

2.2. Energy estimation
In order to achieve an annual primary energy balance of 0 (zero), the ZEB demonstration building aims to realize an ultra-high energy reduction of 75% compared to typical buildings, and the remaining 25% of energy consumption is balanced out in plans by generating power though the use of solar energy generation systems installed on the roofs and walls. (Figure 2)

3. The building outline
The outline of the building used in this research is shown below. (Figure 3)
3.2. Architectural features
The building is located approximately at the center of a R&D institute site, where it functions as an office building for researchers. Additionally, it serves as a demonstration experiment building for practical application of newly developed technologies. The building has conference rooms and display spaces on the first floor, while the second and third floors are used as offices. (Figure 4) Compared to a typical office, this building features an innovative balcony, which not only provides mechanisms for energy conservation such as shading, natural ventilation, and lighting equipment, but also functions as an outdoor workspace to improve the intellectual productivity. To realize an urban ZEB from the perspective of the sustainability of the building itself, we incorporated the following three architectural and structural technologies.

3.2.1. Flat, ceiling-less office space. The flat ceiling surface employing an upstanding beam structure not only enables floor-to-ceiling height to be secured but also functions as a radiation surface for diffusion of natural light and radiant heating and cooling, in addition to eliminating worry about ceiling materials falling. (Figure 5)

4. Overview of equipment design

4.1. Natural ventilation and heating/cooling
For heating and cooling equipment, intending to proactively use natural ventilation and reduce heating and cooling loads by reducing internal heat generation, we made plans to use cogeneration to make ambient heating and cooling highly efficient. In addition, in the design of the personal heating and cooling system, the plans called for a sensor that automatically detects human activity to be used as a base technology, with a self-select feature (adjustment function) for individual persons added to this, in order to provide the appropriate amount of service to the locations where service is needed so as to maximize satisfaction. (Figure 6)
4.1.1. Natural ventilation system. We developed and introduced a system that reduces the energy used for heating and cooling while maintaining a comfortable environment by enabling fresh air to be brought inside in seasons when the outdoor temperature is appropriate, thereby generating air flow by the power of the breeze. Until now, assessment of whether to open or close all natural ventilating openings and windows in office spaces were uniformly carried out based on measured outdoor weather conditions. For this reason, even if a suitable breeze could be taken in through some natural ventilating openings, there were cases in which every natural ventilating opening was left closed. In addition, in the case of manually operated windows, those who stay inside the office cannot determine how much to open the window to allow an appropriate amount of external breeze inside, so in relatively windy weather, those in the office had to use trial and error to determine how much to open the windows. This system assesses whether to open or close natural ventilating openings and windows on an individual basis, thereby realizing a comfortable indoor environment based on the weather and environmental conditions such as wind, air temperature, and room temperature as well as information on people's presence and locations. Based on these results, the system automatically opens and closes the natural ventilating openings; for manually operated equipment such as windows, it displays information showing how much to open such windows on the computer screens of people in the office. Which state of opening and closing will achieve an appropriate indoor environment is assessed by combining analysis of a database containing prior simulation results with consideration to the shape of the building and surrounding block, environmental monitoring data inside and outside the building (wind direction, wind speed, temperature, and humidity), and information on people's presence and locations. As a result, it becomes easy to appropriately bring outdoor breezes inside in order to maintain a comfortable indoor environment.

4.1.2. Radiation heating and cooling system employing exhaust heat. Conventionally, exhaust heat energy has been used for heating and hot water supply. However, for office buildings, where there are few pieces of equipment that use heat throughout the year, there are few application examples, so in fact the utilization rate of exhaust heat is low. The system we developed this time is TABS (Thermal Active Building System), which produces medium-temperature cool water (about 16°C) using low-temperature exhaust heat (about 60°C) as an energy source, in addition to cooling the building shell itself by letting cool water flow through piping embedded in concrete slabs. It also employs a radiative effect from the ceiling surfaces to stably cool the entire space. In addition, during winter, heating can also be performed by allowing the flow of exhaust heat to directly heat the hot water in the piping. (Photo 3) In the ZEB demonstration building, the combination of use of a high efficiency fuel cell for cogeneration with an adsorption refrigeration system, which can produce cool water using low-temperature exhaust heat, aims to dramatically improve system efficiency. (Figure 7)

![Figure 7. Surface temperature distribution of TABS during cooling](image)

4.1.3. Personal air conditioning. This system is a task air-conditioning which positions the fresh air processing function, a major role of heating and cooling, as a major function and integrates an individual adjustment function for airflow volume. There have been a number of conventional personal heating
and cooling systems that have air conditioners for fresh air processing or air volume adjustment mechanisms. But, there are few application examples of systems that include both functions because of the required large scale as well as complexity of control and other factors. The task heating and cooling system we developed this time consists of a personal heating and cooling unit which can adjust to the level of humidity using general-purpose air conditioning equipment for fresh air processing as well as a personal air outlet, which automatically opens and closes. Although our system is compact, it has both a reliable dehumidification function and an individual air volume adjustment mechanism. From the perspective of energy saving, it incorporates a system that allows the amount of fresh air introduced to be controlled appropriately by automatically opening personal air outlets where people are located using a next-generation human activity detection sensor. In addition, since someone who feels hot can boost the amount of blowout air by performing heating or cooling operations from the computer at his or her seat according to personal preference, worker satisfaction increases. (Figure 8)

4.2. Lighting and illumination equipment
Aiming to realize a ZEB, we set a lighting design concept of low illumination intensity task and ambient lighting using a combination of four lights. The system introduces daylight utilization devices; through the development and implementation of low illumination intensity ambient lighting, which uses a combination of optimal lighting controls employing the next-generation sensing technologies of human detection sensors and brightness sensors alongside soft lights, as well as the development and implementation of organic EL task lighting, the system minimizes the amount of energy required for lighting while simultaneously ensuring a sufficient impression of brightness (Figure 9).

Figure 8. Airflow distribution of personal air diffuser

Figure 9. Concept of the lighting system
For conventional task and ambient lighting, an ambient illumination intensity of about 300 lx is necessary. In our plan, we carried out design so as to have a lower illumination intensity of about 200 lx give the same impression of brightness while minimizing the energy requirements for lighting and associated heating and cooling, thereby significantly contributing to realizing a ZEB.

4.2.1 Day-lighting device. Lighting accounts for approx. 20% of the energy consumed in a typical office. Power saving efforts started after the Great East Japan Earthquake lead to promotion of low illumination lighting, which was confirmed not only to reduce the amount of energy required for lighting but also the amount of energy used for air conditioning thanks to the reduction in heat generated by lighting. In addition, when daylight can be used, it was confirmed that even when lights were off, desk work could be performed continuously. In recent years, lighting equipment such as dimming controls and LED lighting has begun to become popular and the importance of reducing energy used for lighting during daylight hours has come under the lens. Most major conventional daylight utilization methods make use of blinds. However, there are issues in which glare is generated on window surfaces, daylight cannot penetrate deep into the rooms, and furthermore blinds obscure the view from the window. This lighting equipment was developed under the following concepts: 1) place lighting equipment on window surfaces on each floor in order to realize an urban ZEB, 2) have lighting catch the sun at every solar altitude using a fixed, maintenance-free structure, and 3) introduce natural light through the ceiling for rooms deep inside the building to improve the level of brightness of the entire room interior. The demonstration building has balconies. While the canopy screens direct glare, the view remains visible and lighting equipment installed on the upper parts of balconies directs natural light. Having a specific curved surface with sections composed of a combination of parabolas, this lighting equipment can respond to the solar altitudes of various seasons and times to let in light. Natural light guided inside rooms always illuminates the ceiling surface, giving a bright impression to the interior space and providing diffused soft light on desk surfaces without glare, thereby both improving the quality of the lighting environment of the room interior using daylight as well as reducing the amount of energy required for lighting. (Figure 10)

![Figure 10. Section of day-lighting device](image)

4.2.2 Brightness control and human detection control for high-efficiency LED lighting. Ambient lighting control is performed using natural light on the ceiling surface, which is guided deep into the room by lighting equipment and upward-facing ultra-high-efficiency LED lighting. During the daytime, when sufficient natural light can be obtained by measuring the quantity of natural light using upward-facing
brightness sensors to control dimming, upward-facing LED lighting is automatically turned off. Although the desk surfaces have a low illumination intensity of 200 lx, the system ensures luminance on the ceiling surface and provides sufficient brightness throughout the room interior. Downward-facing ultra-high-efficiency LED lighting is controlled by T-Zone Saver, a human detection control system, and provides a pinpointed illumination intensity suitable for desk work. The system presumes that work is done on computer monitors and sets the ambient illumination intensity on desk surfaces in the range of 200 to 300 lx.

4.2.3 Organic EL task lights. Organic El task lights are used depending on the type of paperwork and individual preference. An illumination intensity equivalent to 700 lx on desk surfaces can be secured using a combination of task lighting and ambient lighting. Most conventional lighting plans that aim to reduce energy do so by using task lights to curb the illumination intensity of ceiling lighting. On the other hand, when compact, high brilliance illuminants such as LEDs are used, in some cases the comfort of the lighting environment in the office space is impaired by phenomena such as glare and shadows cast by workers' hands. In addition, organic EL lighting panels are becoming popular in decorative lighting, which makes use of both their features of the soft impression given by surface emitting light and the low weight of their panels. However, there have not been any practical lighting systems using organic EL lighting panels that meet the necessary requirements for brightness, color rendering properties, and product life for task lights in offices. The newly developed "Organic EL task light" has been designed to have specifications that allow dimming to be adjusted individually using devices with a maximum output of 500 lx by employing organic EL lighting panels. These panels offer globally leading levels of brightness, product life, and color rendering properties necessary for practical office use. Making use of the features of ultra-thin illuminants, this light is designed to stay out of the way in desk areas. In some cases, task lights impair the brightness of the office space, such as when they cause workers to experience glare; thus, there are restrictions on the extent to which office space can be made low illumination. The organic EL task light uses surface-emitting illuminants and has a soft light distribution that eliminates glare. This task light enables an interior lighting environment which minimizes energy use by making the entire office space low illumination (300 lx --> 200 lx) while giving an impression of brightness in the interior space to maintain the quality of the lighting environment.

4.3. Power source and energy management
The following design concepts are employed: effective use of renewable energy, use of highly efficient power supply, and BCP response.

4.3.1 Photovoltaic cell plan which makes efficient use of the entire building. This plan is designed to maximize solar energy generation by making efficient use of not only the building's rooftop but also the walls.

a) Single-crystal photovoltaic cell panel
Focusing on the amount of power generation, single-crystal photovoltaic cell panels were installed on the rooftop. By using high efficiency panels having a rated power generation efficiency of more than 20% and installing them at a horizontal angle, the amount of power generation was maximized in consideration of shadows. Generated electricity can be interconnected with commercial electric power for use inside buildings as well as stored in batteries as described below or used in other facilities on-site.

b) External walls with organic thin-film photovoltaic cells
In order to realize standalone ZEB in urban areas, electric power generation on rooftops is insufficient, so electricity must also be generated on wall surfaces. Therefore, we focused on organic thin photovoltaic cells, which show promise as a future electric power generation technology. Together with Mitsubishi Chemical Corporation, we jointly developed the building's external wall units, which
generate electricity using organic thin photovoltaic cells, and introduced them as demonstration experiments. These units have the following three features.

First, since they are made of organic materials, their colors can be selected and changed. Currently, the most popular colors for crystal photovoltaic cells (hereinafter, "crystal cell") are black and dark blue. However, other colors of organic thin photovoltaic cells are available. This time, we selected green. Such flexibility has the merit of enhancing the architectural design's degree of freedom.

Second, the units offer freedom with respect to shapes and dimensions. Crystal cell panels are restricted in terms of their shapes and dimensions; thus, it is difficult to install crystal cell panels to match arbitrary window widths. On the other hand, the organic panel has no such restrictions, enabling structures to be made to be as close to the required building module as possible, thereby heightening the design's degree of freedom.

Third, the organic panels are lightweight, which improves workability, and can be integrated with building materials. Since these panels are lighter than most lightweight crystal cell panels, it is easy to flexibly install and remove them from inside the building. When installing typical photovoltaic cell panels on walls, scaffolding is needed outdoors. However, when installation can be carried out inside the building, scaffolding is not needed, so reduced construction costs can be expected.

Other excellent features of these units, such as the fact that power generation can be carried out even on cloudy days with low amounts of solar radiation, are being verified by measuring various types of data, including power generation amounts. (Figure 11)

### 4.3.2 Cogeneration using high-efficiency fuel cells

The ZEB demonstration building uses a cogeneration system employing high-efficiency fuel cells in order to increase energy efficiency. We introduced a Solid Oxide Fuel Cell (SOFC), which is a piece of demonstration equipment. Operations are being carried out in the building alongside demonstration experiments. This piece of equipment, which is still in development, aims to achieve a power generation efficiency of 48% and overall efficiency of 90%. Since operation is basically continuous (base operation), efficient use of exhaust heat during electric power generation (matching to air conditioning loads) is the key. The operating plan for the heat source, in which the hot water heat storage tank is designed as a buffer, is under experimentation.
4.3.3 Power supply plan that gives consideration to BCP response. After the earthquake disaster, demand has been increasing for buildings which are not as dependent on energy supply. Since a ZEB has lower energy consumption and high ratios of natural energy and power generation, it presents less risk in an emergency situation and good BCP response. In the ZEB demonstration building, in the event of a blackout, we have prepared plans to connect 20% of the rooftop photovoltaic cell panels to a battery system for use as a base for BCP response and provide electricity for specific loads, such as lighting and power outlets, on the first floor. It is possible to use power generated using photovoltaic cell panels during the day when solar radiation can be sufficiently captured and compensate for load changes using lithium ion batteries, and then to use the electric power from such batteries at night.

4.3.4 BEMS. Regarding energy management issues for buildings, in addition to the trend toward CO2 reduction, because of the energy supply crunch and electric power price hike, power-saving countermeasures have become more important. In order to provide a mechanism to continuously support building operations and offer energy-saving proposals by preparing easy-to-understand visualizations of energy information as well as taking the lead in administering such data, we have been developing T-Green BEMS as our company's unique Energy Management System (EMS). We have also introduced this system in the ZEB demonstration building as a core system for energy management. T-Green BEMS is configured to perform the following functions: (i) monitor and control energy generated from photovoltaic cell panels, fuel cells, and micro cogeneration, (ii) skillfully store that energy in batteries and heat storage tanks, and (iii) use that energy inside the building cleverly and efficiently. Energy consumption is measured in detail by type of use (such as lighting, power outlets, heat sources, heating and cooling, ventilation, and sanitation) and per area. In addition, (iv) by using a mode of operation which responds to demand and supply adjustment signals and also considers the environmental comfort of those in the building, T-Green BEMS assesses how to facilitate efficient operations for the entire building, and also (v) coordinates sending and receiving of electricity to and from energy infrastructure (power system) as necessary. In addition, we incorporated ZEB-navi as a visualization tool in T-Green BEMS; this tool clearly displays whether energy consumption is achieving net zero. Finding a good way to understand the balance between generated renewable energy and used energy at a glance enables the current situation and future forecasts to be understood easily and is a valuable step in moving the process of achieving ZEB forward. (Figure 12)

5. Operational results

A comparison of the energy balance record for each fiscal year is shown in Figure 13 (a) as the energy balance record for 3 years. As a result of the first year of operation, the energy consumption was 463 [MJ/m²], the generated energy was 493[MJ/m²], and the annual energy balance was 0 or more, and after that ZEB operation was continued. Next, the energy balance record for each month is shown in Figure 13 (b). Compared to general buildings, we are actively utilizing natural energy, and the impact on
weather condition consumption and generation energy is remarkable. For example, in September and October of 2016, the amount of generation energy by PV is small because of sunlight hours were short (bad weather such as heavy rain). Also, the influence of the utilization rate of the building is great, and in the period of completion in the first period of completion in the period of June, July, August 2014, visitors are more and energy consumption is large.

6. Conclusion
This study for realizing and popularizing urban ZEB has just begun. However, we have already received a response that exceeds our expectations, and a significant number of people have used and visited our building after its completion. And we reported about performance and the results of detail analysis and evaluation based on the accumulated data. From now on, we will organize the tasks extracted by this research and resolve them step by step.

References
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