Energy-Saving HVAC System and Design Methods Utilizing Medium-Temperature Chilled Water for Office Buildings

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Abstract. This paper presents an energy-saving HVAC system and design method using medium-temperature chilled water for office buildings. The proposed heat load calculation method focuses only on necessary areas, reducing air volume load compared to conventional methods. It separates heat load calculations for interior and ceiling spaces. The air volume is calculated based on the interior load, while the ceiling space load—mainly from lighting and skin load—is included in coil load but excluded from air volume load. Typically, air cooling uses chilled water at around 7°C. This system adopts a two-step cooling process using medium-temperature chilled water and chilled water to increase chiller outlet temperature and improve efficiency by approximately 25%. Outside or return air is first pre-cooled with medium-temperature chilled water, then cooled further to the required temperature. In this system, outside air is cooled to 16°C and supply air to 12°C. About 50% of the total heat load can be handled by medium-temperature chilled water, allowing the chiller to operate at a higher outlet temperature and achieve greater efficiency.

1 Introduction

In large-scale high-rise tenant office buildings located in urban centers, heat source and air-conditioning systems have remained largely unchanged for nearly 30 years. The typical configuration involves accepting district heating and cooling and adopting single-duct variable air volume (VAV) systems on each floor. In many cases, improvements are limited to perimeter air-conditioning strategies.

Recently introduced systems such as underfloor air distribution, radiant air-conditioning, desiccant air-conditioning, and geothermal energy utilization are feasible for small- to medium-sized buildings. However, due to tenant requirements and building scale, these systems are not well-suited for large-scale high-rise tenant office buildings.

On the other hand, the use of district heating and cooling and the area-wide utilization of energy face several challenges: difficulty in forming consensus among many stakeholders, lack of coordination between building-side and supply-side operational control, and HVAC systems being designed based on existing supply conditions rather than building-specific needs. These challenges are especially significant when the building and district heating/cooling providers belong to different corporate groups or when existing district systems are involved.

In recent years, from the perspectives of ESG investment and the SDGs, it has become an urgent issue to create smart wellness office environments that not only improve environmental and energy performance but also enhance the health and comfort of occupants.

Therefore, the target building of this study aims to realize new future value in high-rise tenant office buildings through co-creation—value that has not existed before—and to contribute not only to individual buildings but also to the improvement of the entire urban area, including adjacent districts beyond the boundaries of the development site.

This study focuses on a high-rise tenant office building that embodies an urban environmental design and smart wellness office concept extending beyond the development site, and evaluates the operational performance of an energy-saving HVAC system and design methods utilizing medium-temperature chilled water for office buildings.

2 Research methods

2.1 Building overview

Figure 1 shows the north-side exterior view and the sectional composition of the building's functions. Table 1 presents an overview of the building. Completed in 2017, the building has a total floor area of approximately 178,000 square meters and consists of 38 floors. Its primary functions include office spaces, conference facilities, retail areas, and residential units.

In addition, vertical louvers with solar shading and natural ventilation functions are installed on the exterior of the high-rise structure. These louvers enable wind-catcher-type natural ventilation, contributing to both energy efficiency and indoor environmental quality.

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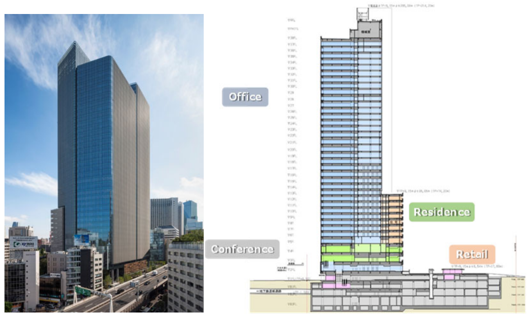

Fig. 1. North side appearance and sectional composition of building functions.

Table 1. Building overview.

Building scale	38th and 3rd underground
Site area	16,000 m^2 (172,220 ft^2)
Total floor space	178,000 m^2 (1,916,000 ft^2)
Structure	Steel framed, Steel reinforced concrete structure.
Building use	Office, Conference, Retail, and Residence
Completion date	August 2017

2.2 HVAC system with energy-saving and CO2 reduction technologies

2.2.1 Three-zone air conditioning system for perimeter, interior, and core side areas

Figure 2 illustrates the air-conditioning zoning plan for the standard floor. The air-conditioning system for the standard office floors is designed to accommodate up to five tenants per floor. It is divided into three zones:

the perimeter zone, which supports simultaneous heating and cooling for private rooms near the windows,

the interior zone, which primarily serves open-plan areas with seasonal switching between heating and cooling, and the core-side zone, which provides air-conditioning for private rooms located near the building core.

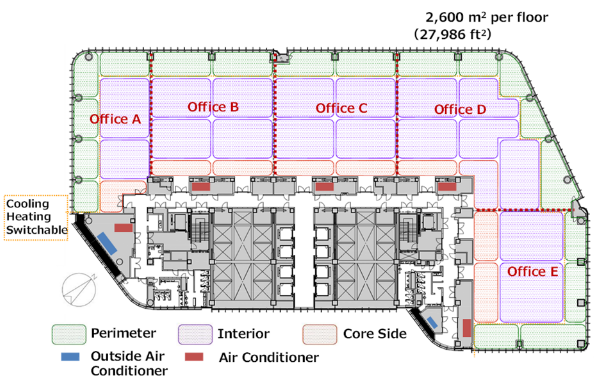

Fig. 2. Standard floor air-conditioning zoning diagram.

2.2.2 Multi-duct HVAC system with separate outdoor air and indoor load processing

Figure 3 illustrates the system flow. The system employs a functionally divided multi-duct HVAC configuration, in which outdoor air supply (with humidity control) and temperature control functions are separated and can be flexibly combined to meet diverse operational needs.

The outdoor air and humidity control function enables variable ventilation, ranging from full outdoor air to minimum supply. Dehumidification and humidification are performed by a dedicated outdoor air handling unit. Areas with high occupant density can be accommodated by increasing the outdoor air volume. The temperature control function allows for flexible thermal adjustment, even under winter conditions where heating and cooling coexist. By combining supply air temperatures and airflow volumes of warm and cool air, the system can regulate discharge temperature through mixing or switching. Areas requiring year-round cooling are served by a continuous supply of cool air.

To reduce the outdoor air load, the system utilizes a total heat exchanger and optimizes outdoor air volume based on CO_2 concentration. Fresh air is supplied to the five-section tenant area via two interconnected outdoor air conditioners. By linking the two units through ducts and controlling their operation based on CO_2 levels, the system enables energy-efficient operation at reduced airflow volumes.

When only minimal outdoor air is required—such as during low occupancy—one unit can be stopped, allowing the other to operate at its minimum airflow rate. This configuration enables operation below the typical minimum airflow of 30%, which would not be possible if the units were not connected.

Each toilet exhaust fan is installed in pairs and controlled based on occupancy sensors in the toilets and CO_2 concentration in the office area. When unoccupied, the exhaust rate is reduced from 10 air changes per hour to 5, enhancing the effectiveness of the total heat exchanger.

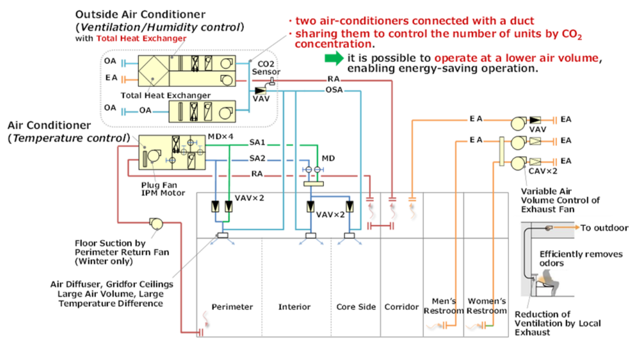

Fig. 3. Functionally Differentiated Multi-Duct Air-Conditioning System.

2.2.3 Air-conditioning system using medium-temperature chilled water

Figure 4 presents a schematic overview of the air-conditioning system using medium-temperature chilled water. In general, air cooling uses chilled water at around 7 ℃. This system uses medium-temperature chilled water at 15 ℃. the use of medium-temperature chilled water raises the chiller outlet temperature and allows it to operate with high efficiency.

Outside air or return air is first pre-cooled with medium-temperature chilled water, and then further cooled to the required temperature using standard chilled water. In this system, outside-air is 16 ℃, and Air conditioner supply air is 12 ℃ by using medium-temperature chilled water system. Approximately 50% of the cooling energy can be provided by medium-temperature chilled water without changing the total heat load, contributing to significant energy savings.

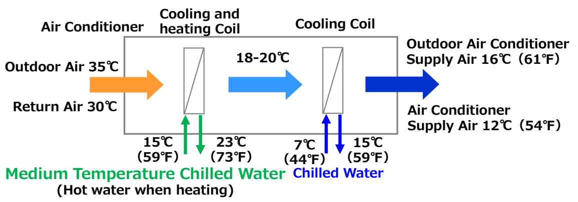

Fig. 4. Schematic overview of the air-conditioning system using medium-temperature chilled water.

2.2.4 Medium temperature chilled water transport system

Figure 5 presents the medium temperature chilled water transport system. This four-pipes transport system switches between medium temperature chilled water and hot water depending on the season. The thermal transport system is divided into three vertical zones based on building height, and further separated into chilled water and hot/chilled water systems according to the type of heat transfer medium, resulting in a total of six supply systems.

While the system primarily uses an indirect supply method, the chilled water system for the lower floors is directly connected to the district heating and cooling (DHC) network to reduce energy required for thermal transport.

The remaining five systems utilize variable flow control via secondary pump groups, each consisting of three or four pumps. All secondary pumps are equipped with IPM (Interior Permanent Magnet) motors, and their operation is controlled by setting the supply pressure in coordination with the air-handling units' DDC (Direct Digital Control) systems.

The heat transfer pumps feature variable water volume control to enable energy-efficient operation. Chilled water, medium-temperature chilled water, and steam are supplied by the district heating and cooling (DHC) network. The medium-temperature chilled water supply is coordinated between the DHC and the building-side control system.

2.2.5 Area-wide energy optimization enabled by expansion of DHC coverage

Figure 6 shows district heating and cooling(DHC) area and DHC plant layout. The existing district heating and cooling had the main plant and sub-plant. It was rezoned and expanded, and a third plant and co-generation system were constructed in this building.

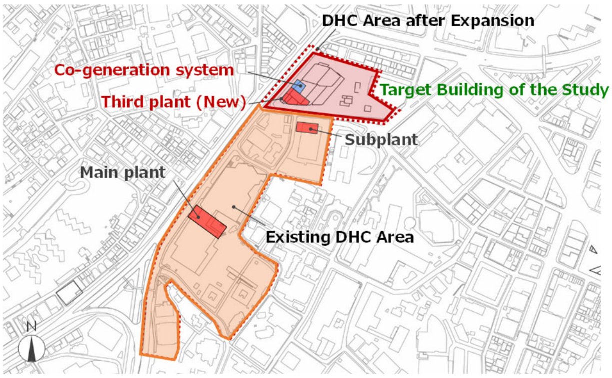

Fig. 6. DHC Area and Plant Layout.

Figure 7 presents a conceptual diagram of the overall energy supply system. Due to insufficient supply capacity of the existing plants, a third plant was newly installed within the building.

To support a self-sufficient, energy-based urban development, a high-efficiency cogeneration system (CGS) was newly installed in the building to compensate for the shortage of thermal energy sources.

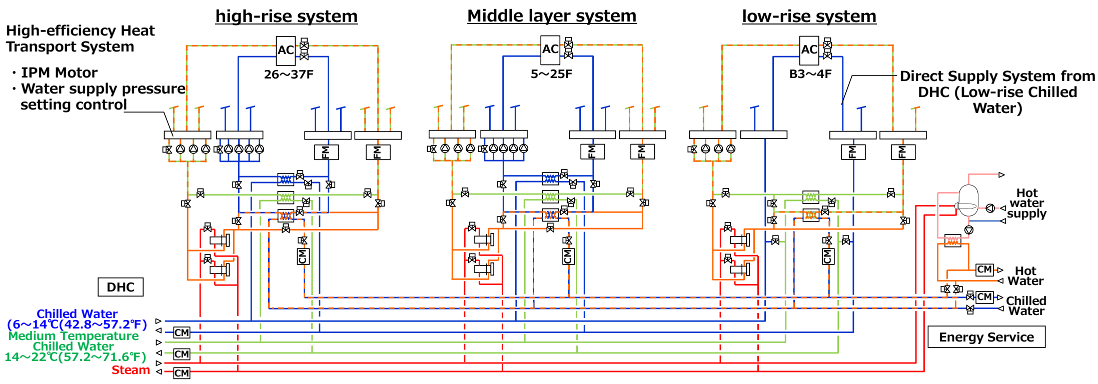

Fig. 5. Medium temperature chilled water transport system.

The steam generated from the CGS waste heat is shared among the three DHC plants, contributing to reduced gas consumption by the steam boilers in the main plant.

Chilled water is coordinated between the existing sub-plant and the newly installed third plant. During peak periods, surplus capacity from the sub-plant is utilized in the redevelopment area. Conversely, when the third plant has surplus capacity, it supplies high-efficiency thermal energy to surrounding existing buildings, realizing a new energy supply system that maximizes energy efficiency.

As part of the energy service business, a high-efficiency gas engine cogeneration system and a hot water-fired absorption chiller were installed in the building. Electricity, hot water, and chilled water are supplied to the building, while steam is supplied to the district heating and cooling (DHC) system.

Hot water from the CGS is supplied year-round and used for heating and preheating/heating hot water during winter. Chilled water from the hot water-fired absorption chiller is supplied only during summer and intermediate seasons. Through heat exchangers in the CGS system, chilled water is supplied to the secondary side of the building. Chilled water is controlled by flow rate, and hot water is operated in series with steam to cover the base load of hot and chilled water used in the building. The system operates under a DSS (daily start and stop) mode, with two units running during summer and winter, and one unit during intermediate seasons.

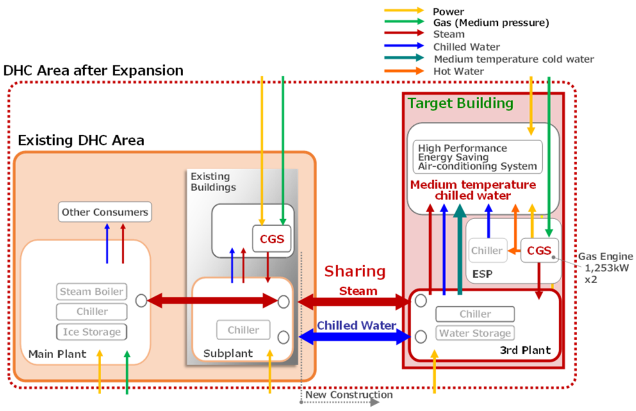

Fig. 7. Overall energy supply system.

2.3 Method

The building's central monitoring system utilizes a cloud-based BEMS (Building Energy Management System), which is accessible from office PCs to support energy-efficient operations. The BEMS manages energy usage, provides services for office users, and supports facility maintenance. Energy management functions include the collection and analysis of data from indoor measurement points—such as temperature, humidity, and meter readings—which can be accessed via the internet.

Using data collected through the BEMS, the system's performance was analyzed and verified.

3 Results

3.1 Heat load calculation in new air-conditioning design method

Figure 8 presents the conventional heat load calculation, while Figure 9 presents the heat load calculation in CO2-saving air-conditioning design method

In this heat load calculation, the thermal loads of the interior space and the ceiling void are evaluated separately. The air volume required for air conditioning is determined based solely on the interior heat load. While the ceiling space includes lighting and envelope (skin) loads, these are considered only in the coil load calculation and excluded from the air volume estimation.

As a result, the air conditioning system is designed to condition the occupied interior space, but not the ceiling void. For instance, the interior temperature is maintained at 26°C, whereas the ceiling space temperature may reach approximately 30°C. The primary objective is to control the thermal environment of the living and working areas, rather than the ceiling void. Consequently, the required air volume for air conditioning can be reduced when the ceiling space does not require direct thermal control.

Regarding heat generation from lighting fixtures, an investigation was conducted in collaboration with the lighting manufacturer to determine the distribution of heat. It was found that approximately 20% of the heat is emitted below the ceiling, while 80% is released into the ceiling void.

By applying this revised heat load calculation method, the required air volume for air conditioning was reduced by approximately 31% compared to conventional design approaches.

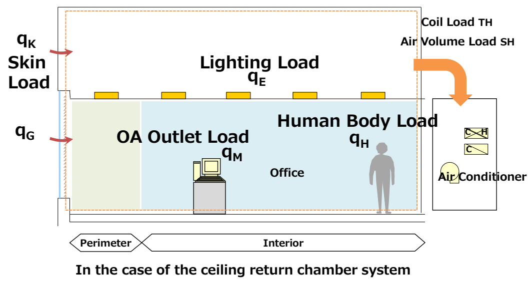

Fig. 8. Conventional heat load calculation.

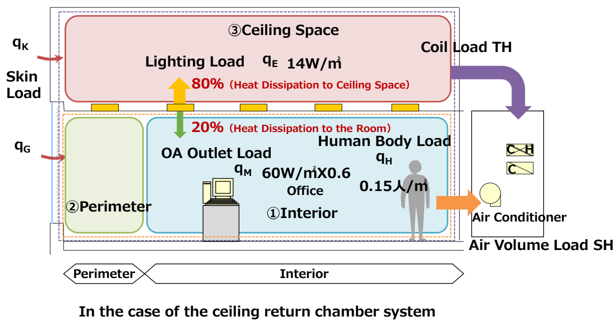

Fig. 9. Heat load calculation in CO2-saving air-conditioning design method.

Figure 10 illustrates the reduction effect achieved through the CO_2-saving air-conditioning design method. This approach resulted in a 48% reduction in energy consumption compared to the standard system. The standard system refers to a conventional configuration designed to handle the entire room heat load. The calculation and evaluation were based on actual operating hours and air volume data from this building, with the power consumption of the standard system estimated accordingly. This reduction effect also includes the contribution of the low-temperature air supply system.

3.2 Optimal outside air volume control system

Figure 11 presents the annual hourly operation ratio of outdoor air conditioner units. The ratio of operating outdoor air handling units was analyzed across four representative floors during weekdays between 7:00 and 22:00. The number of units in operation was controlled in accordance with the building load, and it was observed that single-unit operation occurred in slightly less than 10% of cases even during daytime hours.

Figure 12 shows the annual hourly operation ratio of toilet exhaust fans. The ratio of operating toilet exhaust fans was analyzed across four representative floors during weekdays from 7:00 to 22:00. While operation with four and two units accounted for the majority of cases, instances of three-unit operation were also observed. These findings indicate that the number of operating units was appropriately controlled based on the occupancy status of the toilets. During periods of reduced outdoor air handling unit load, such as in the early morning and late evening, it was confirmed that the control of toilet exhaust fan operation was functioning properly. By regulating the number of operating toilet exhaust fans, the exhaust airflow through the total heat exchangers increased, thereby enhancing the overall heat exchange efficiency.

Figure 13 presents the reduction effect achieved through the optimal outside air volume control system. The standard system shown in the graph does not have a variable air volume(VAV) system. The outside air volume control system reduced the outside air load by about 73%.

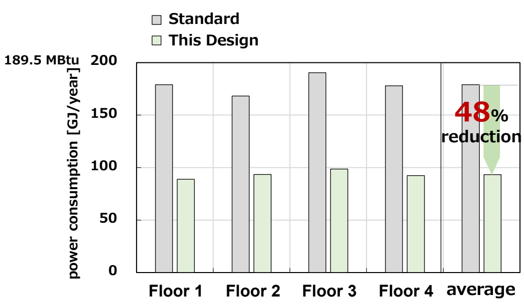

Fig. 10. Reduction effect by CO2-saving air conditioning design method.

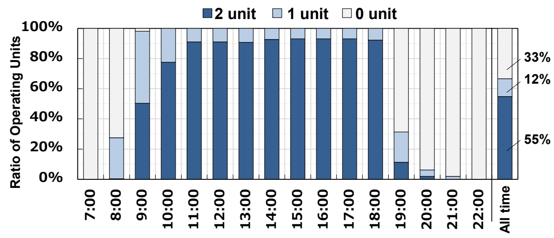

Fig. 11. Annual hourly operation ratio of outdoor air handling units.

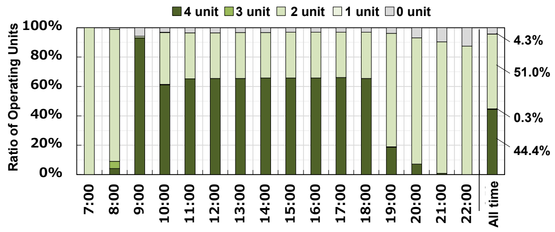

Fig. 12. Annual hourly operation ratio of toilet exhaust fans.

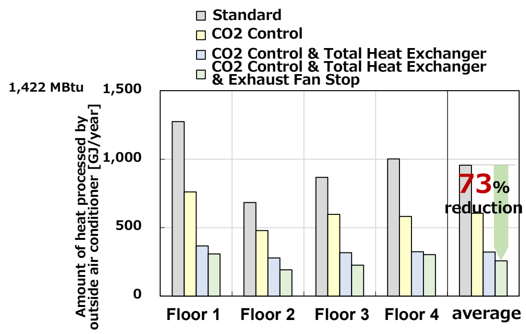

Fig. 13. Reduction effect by optimal outside air volume control system.

3.3 Operating Efficiency of Chiller Using Medium Temperature Chilled Water

Figure 14 presents the load factor and unit COP of the centrifugal chiller. The average energy efficiency (COP) for chilled water was 6.4, while that for medium-temperature chilled water was 9.0. High-efficiency operation using medium-temperature chilled water was confirmed.

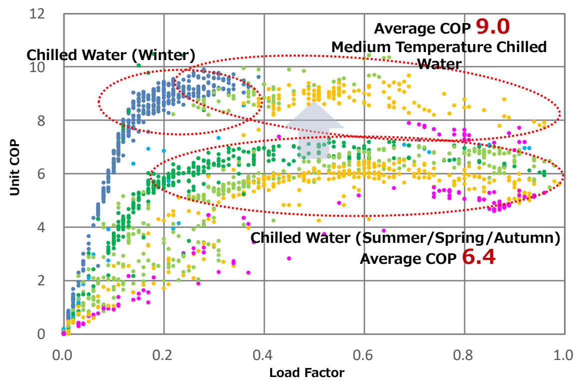

Fig. 14. Load factor and unit COP of centrifugal chiller.

Figure 15 presents the annual steam supply and demand balance between plants. The district heating and cooling (DHC) system facilitates heat sharing and exchange among multiple plants, with priority given to the operation of the newly constructed, high-efficiency third plant. As a result of steam heat exchange from the combined heat and power (CGS) system, approximately 4 TJ/year (3,791 MBtu) of thermal energy was supplied from the new plant, accounting for 6% of the total heat exchange. This centralized steam supply from the third plant significantly reduced reliance on older, less efficient boilers, thereby contributing to overall system efficiency.

Figure 16 presents the annual chilled water supply and demand balance amang the plants. The highly efficient third plant is capable of supplying chilled water to the existing sub-plants. Conversely, during peak demand periods, the sub-plant contributes by supplying chilled water back to the third plant, enabling mutual support and load balancing. Through this chilled water exchange, approximately 16 TJ/year (15,165 MBtu) of energy was supplied from the third plant, and 3 TJ/year (2,843 MBtu) from the existing plant, together accounting for 32% of the total heat exchange. This collaborative operation between plants significantly enhanced overall system efficiency and contributed to energy savings.

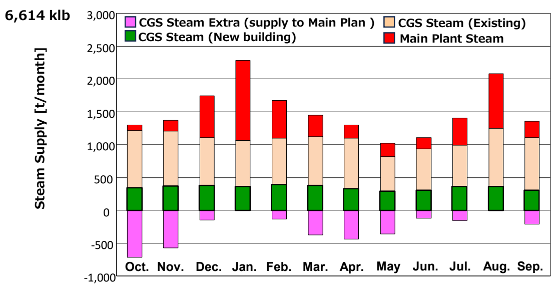

Fig. 15. Annual steam supply and demand balance amang the plants.

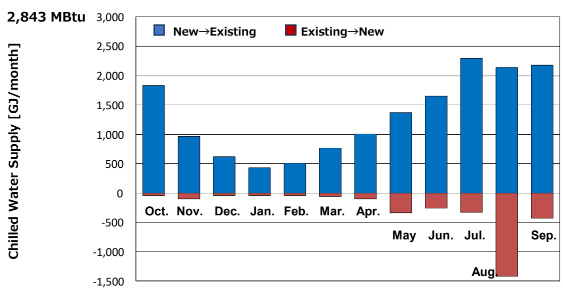

Fig. 16. Annual chilled water supply and demand balance amang the plants.

3.4 Primary energy consumption unit and ZEB evaluation

Since ZEB (Net Zero Energy Building) evaluations are fundamentally conducted on individual buildings, it is challenging to assess energy-saving initiatives that extend beyond the building boundary—such as area-wide energy utilization models like the one presented in this study.

Using primary energy consumption intensity as the evaluation metric for ZEB, a case study was conducted based on actual performance data. In this study, a modified conversion factor for "externally supplied thermal energy" from district heating and cooling (DHC) systems was applied. This factor accounts for the energy-saving effects of area-wide utilization and the use of medium-temperature chilled water systems. The evaluation was performed under different boundary conditions to examine the impact of these factors.

Figure 17 presents the boundary setting patterns used for ZEB evaluation. Three plant efficiency scenarios were assessed by defining different system boundaries. Revision 1 evaluated the overall DHC system, revealing an improvement in the primary energy COP from 0.75 to 0.787 following the construction of the third plant and the implementation of heat exchange. Revision 2 focused on the sub-plant and the third plant. Revision 3 examined the performance of the third plant and the combined heat and power (CGS) system within the newly developed building facilities.

Figure 18 presents the primary energy consumption intensity and the ZEB evaluation results. An energy assessment was conducted for this building, which incorporates various energy-saving technologies. Although the amount of energy reduction varied depending on the boundary conditions used, the overall reduction effect was approximately 50%.

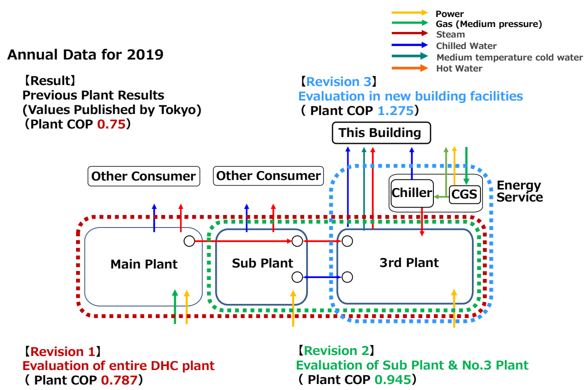

Fig. 17. Boundary setting pattern for ZEB evaluation

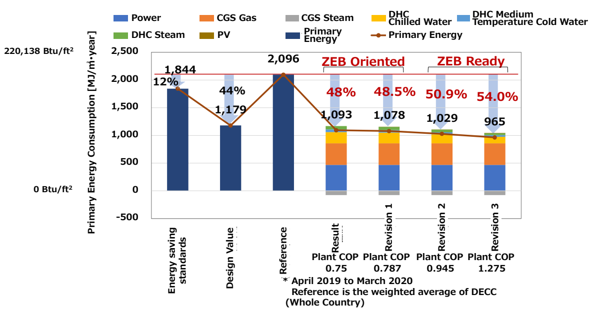

Fig. 18. Primary energy consumption unit and ZEB evaluation.

4 Discussion

This study demonstrated the effectiveness of a CO_2-saving air-conditioning design method and associated control strategies in reducing energy consumption and improving system efficiency within a large-scale building equipped with a district heating and cooling (DHC) system.

4.1 Heat load calculation and air volume reduction

By separating the heat loads of the interior space and the ceiling void, the revised calculation method enabled more targeted cooling. Since the ceiling void was not directly conditioned, the required air volume was reduced by approximately 31%. The analysis of lighting heat distribution—showing that 80% of the heat is released into the ceiling void—supported this approach.

4.2 Outside air volume control

The number of operating outdoor air units and toilet exhaust fans was adjusted based on building usage. This control strategy reduced the outdoor air load by approximately 73% compared to conventional systems without variable air volume (VAV) control. The system responded effectively to fluctuations in demand throughout the day.

4.3 Medium-temperature chilled water efficiency

The use of medium-temperature chilled water improved chiller performance, with the average COP reaching 9.0 compared to 6.4 for standard chilled water. These results demonstrate that medium-temperature operation can significantly enhance cooling efficiency.

4.4 Heat exchange amang the plants

The DHC system enabled heat sharing among multiple plants. The newly constructed third plant supplied steam and chilled water to other plants, reducing reliance on older, less efficient equipment. Steam exchange accounted for 6% and chilled water exchange for 32% of the total, contributing to load balancing and improved overall system efficiency.

4.5 ZEB evaluation and boundary effects

ZEB evaluations typically focus on individual buildings, making it difficult to assess broader energy-saving efforts. In this study, a modified conversion factor was applied to reflect the benefits of shared energy use and medium-temperature chilled water. Depending on the evaluation boundary, the primary energy COP improved from 0.75 to 0.787, and the total energy reduction was approximately 50%.

While these energy-saving technologies have the potential to be applied to other buildings, the evaluation conducted in this study was based on operational data from a single building. Therefore, to verify the broader applicability of these methods, further research is required across various building types and climatic conditions.

5 Conclusion

This study introduced energy-saving HVAC design methods applicable to office buildings, demonstrating significant improvements in system efficiency and reductions in energy consumption.

A revised heat load calculation method, which targets only the zones requiring temperature control, reduced the required air volume for air conditioning by approximately 31% compared to conventional approaches.

The air-conditioning system using medium-temperature chilled water, improving chiller efficiency by approximately 25%.

Two outdoor air-handling units operating in a shared configuration enabled optimal control of outside air volume, resulting in a reduction of outdoor air load by approximately 73%.

These results highlight the potential of integrated HVAC design strategies to achieve substantial energy savings in office buildings, contributing to both environmental sustainability and operational efficiency.

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