Net Zero Energy Factory: Developing an evaluation framework and its introduction to a manufacturing factory to achieve net zero energy

1. Introduction

In [redacted], [redacted] Electric Industry Company, Limited [redacted] embarked a new manufacturing factory construction project (Fig. 1). The construction phase began in June 2021 and was completed in April 2022, and operation began in May 2022. The factory is a two-story building and has a total floor area of 18,837.72 m² (202,767.5 ft²), located in [redacted].

Fig. 1 Exterior (left) and interior (right) of the factory

In addition to solar power generation, substantial energy savings in air conditioning, ventilation, and lighting systems have enabled this factory to be certified as [redacted]'s first Net Zero Energy Building (ZEB) among large-scale manufacturing factories. Moreover, an innovative

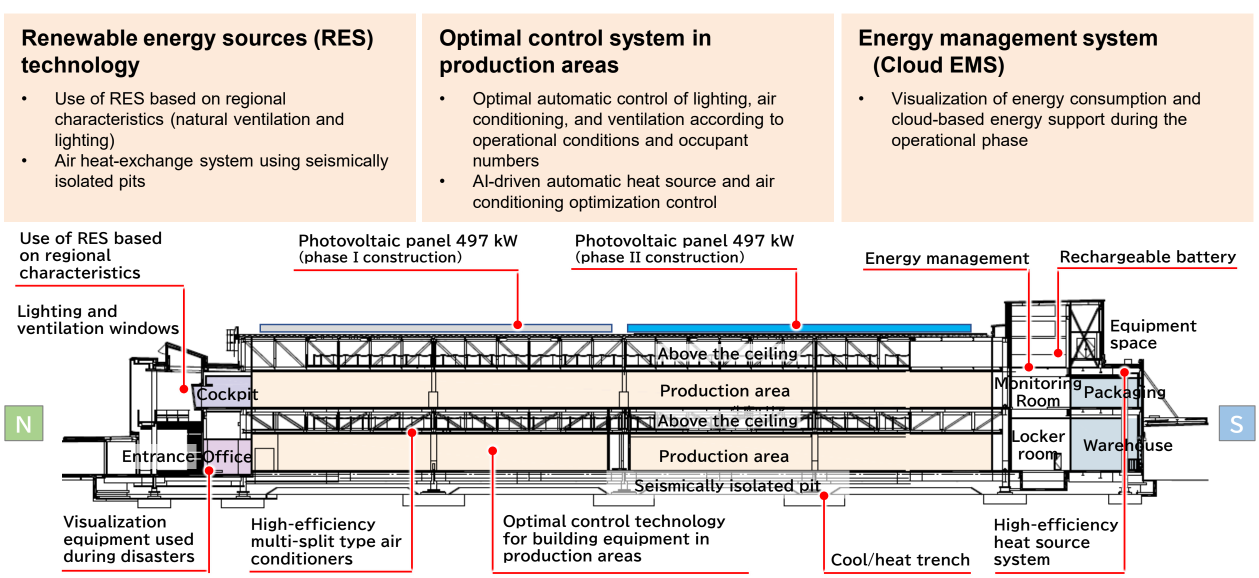

Fig. 2 Summary of energy-saving technologies implemented in the factory

energy evaluation framework, called the Net Zero Energy Factory (ZEF), was independently developed and implemented, establishing a pioneering factory model that is unparalleled globally.

2. Energy efficiency

The factory was designed to reduce energy consumption substantially in high-energy-consuming factories, without relying solely on renewable energy sources. Fig. 2 shows a summary of the energy-saving technologies implemented to reduce the building heat load, including passive technologies such as a air heat-exchange system using seismically isolated pits. The latest high-efficiency equipment, control technologies, and energy management systems are also employed.

2.1. Optimal control technology for building equipment in production areas

In typical manufacturing factories, building equipment systems, including air conditioning and ventilation, are often operated at the design airflow rates and kept at a constant rate. This is usually based on the maximum heat load of the manufacturing equipment and ventilation, resulting in high energy consumption. To address this problem, the factory implemented optimal control technology for the building equipment systems according to the production activity status, thereby achieving energy savings.

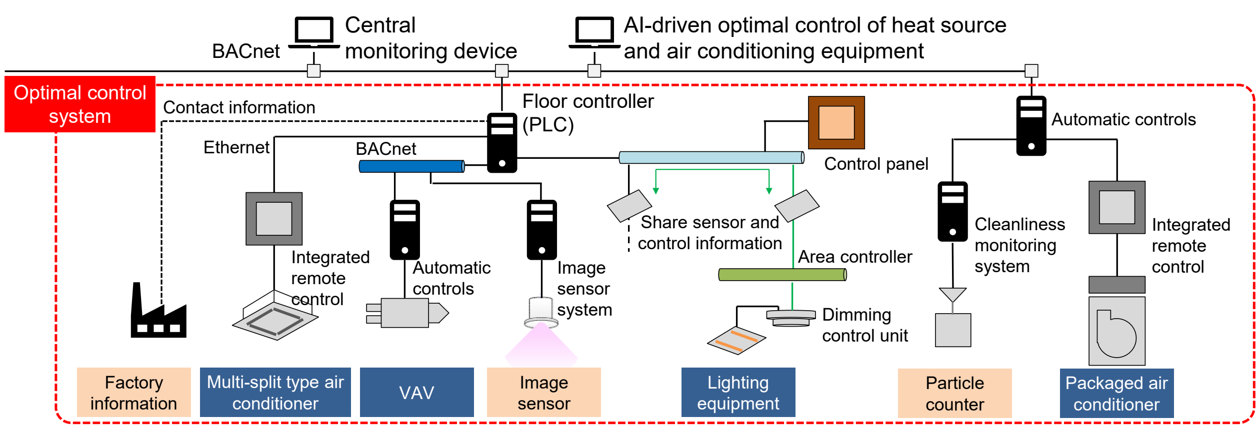

Fig. 3 System overview of optimal control technology

Fig. 3 shows the system overview of the optimal control technology. The data for the control equipment and the input data used for its regulation are accumulated in the floor controller (programmable logic controller). The input data are used to control multi-split type air conditioners and variable air volume (VAV) systems for air handling units and lighting equipment. In addition, cleanliness monitoring in the cleanroom and airflow control of the packaged air conditioner for equipment are performed in an independent control system and these data are accumulated via BACnet in the central monitoring device.

Table 1 shows the control equipment and the input data used for controlling the equipment. Lighting, ventilation, and air conditioning in the production areas are controlled using image sensors and particle counters. Image sensors are used to detect the number of occupants and particle counters are used to monitor the cleanliness level.

Table 1 Control equipment and input data used for optimal control

Input data	Detect item	Control		Details
		Equipment	Content	
Image sensor	Occupant number in each area	Lightning	Dimming control	300 lux when occupied, lights off when unoccupied (can be adjusted to 50 lux when unoccupied)
		Ventilation (VAV)	Control of air volume	Calculate airflow based on occupancy and measure CO_2 concentration. If the CO_2 level is satisfactory, reduce airflow
		Air conditioner (multi-split type air conditioner)	Temperature relaxation and operation mode switching control	Set temperature → Relax by 2.0℃ → Fan mode → Stop
			Refrigerant evaporation temperature control	Adjust evaporation temperature based on required dehumidification from 1 ℃ to 9 ℃ to 14 ℃
Particle counter	Level of cleanliness	Air conditioner (PAC for equipment)	Control of air volume	Reduce airflow below Class 100,000 and the range of the presetting temperature
Production equipment	Equipment status	Local exhaust (VAV)	Control of air volume	Turn local exhaust on/off and adjust airflow based on production equipment status
Production schedule		Outdoor air handling unit	Scheduled operation control (central monitoring)	Control the operation of the air handling unit based on the production schedule

Fig. 4 (a) shows an example of the optimal control technology, which can reduce unnecessary energy consumption substantially in production areas without affecting the quality or quantity of products, while maintaining the safety, comfort, and productivity of employees. Fig. 4 (b) shows the weekly ventilation airflow as performance data. The airflow for each VAV system decreased mainly in the early morning and at lunchtime (12:00–13:00). This resulted in a reduction in energy consumption of approximately 41% during the hour that the air handling unit was in operation. In addition, the exhaust fan power consumption was reduced by approximately 83%. This control reduced overall energy consumption considerably. There was also a reduction in the energy consumption of the heat source owing to the reduced airflow.

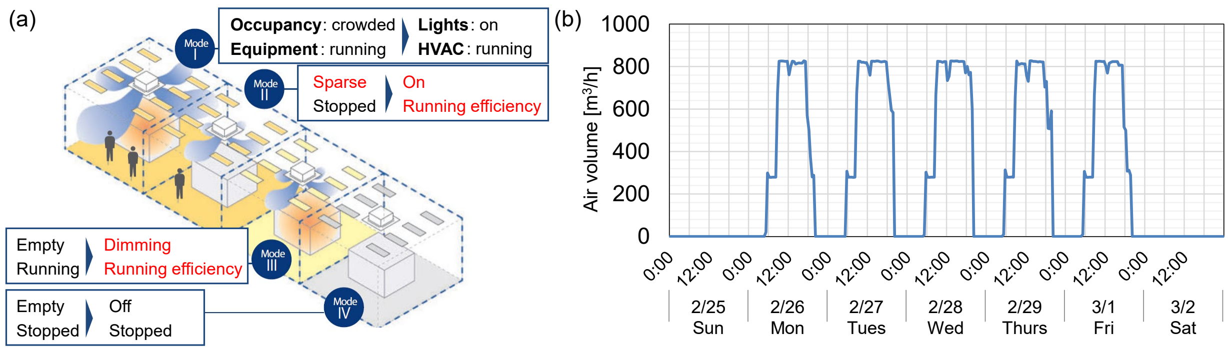

Fig. 4 (a) Example of the optimal control technology and (b) ventilation airflow of VAV

2.2. AI-driven automatic optimal control technology

The optimal control technology has been improved further in the factory by the development of a technology that uses AI to predict energy loads and enable automatic optimal control. The system uses a data-driven approach to predict solar power generation and energy consumption by integrating weather data, production equipment schedule data, and historical operation data (Fig. 5 (a)). The system uses the predictions to control the optimal operation modes and settings for heat sources and air conditioning systems automatically. Furthermore, accumulating annual operational data and incorporating the data into feedback loops enables the system to make predictions that are more precise, resulting in greater energy savings. This approach allows the factory to achieve additional energy efficiency levels that would have been challenging to accomplish through knowledge-driven methods alone, such as relying solely on the experience and intuition of facility managers.

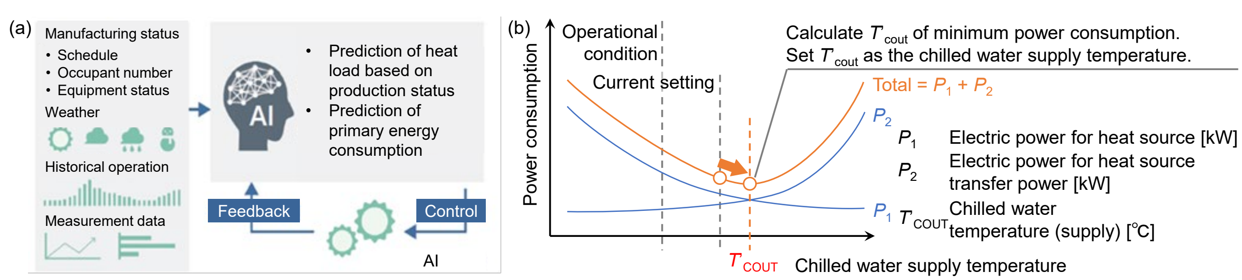

Fig. 5 (a) Outline of the energy prediction method and (b) relationship between the power consumption of the cooling heat source unit and the power required for transport by pump

The energy load prediction method is based on just-in-time (JIT) prediction, which is a statistical machine learning approach. Because JIT prediction learns from limited data and adapts to rapid changes, this method is particularly well-suited to manufacturing factories where there are frequent changes in production lines or operating schedules.

The control system includes optimization of the chilled water supply temperature. There is a trade-off relationship between the power consumption of the cooling heat source unit and the power required for transport by pump, depending on the chilled water supply temperature. In standard cooling heat source systems, an increase in the chilled water supply temperature typically increases operational efficiency, which reduces power consumption. However, as the chilled water supply temperature increases, the efficiency of heat exchange between the air handling unit coils and the supplied air decreases. This decrease results in an increased flow rate of chilled water, which in turn requires greater transportation power from the chilled water pump.

In contrast, the control system models this relationship quantitatively (Fig. 5 (b)), and the optimal chilled water supply temperature is determined and controlled to minimize total power consumption across the cooling heat source system based on the AI-predicted heat load. This approach increases the overall coefficient of performance of the system.

Fig. 6 shows the temperatures and temperature differentials of the chiller supply and return for August 2022 and August 2023, respectively. In August 2022, without automatic optimal control, the chilled water supply temperature was maintained at approximately 9 °C (48 °F). This constant chilled water supply temperature reflects standard operation because supply water temperatures are usually constant in conventional cooling systems. The average temperature differential between the chiller supply and return was approximately 3 °C (37.4 °F), which was smaller than the initial design settings.

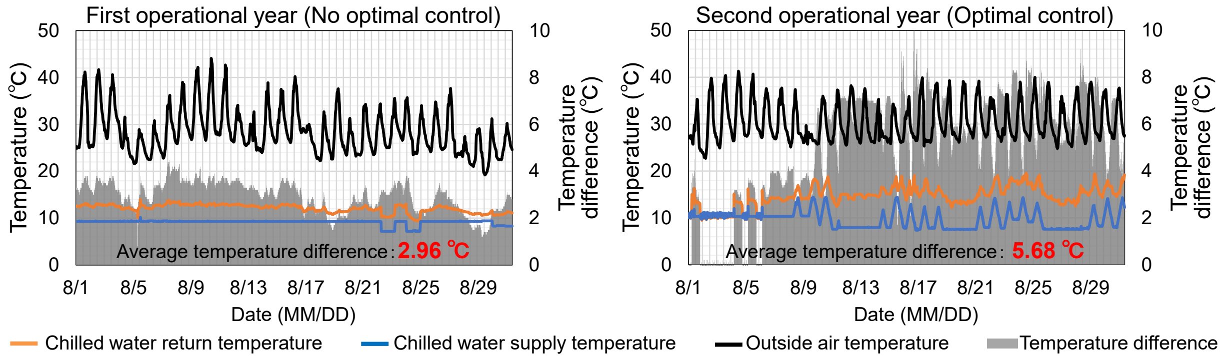

Fig. 6 Temperatures and temperature differentials of the chiller supply and return

In contrast, the automatic optimal control in August 2023 resulted in variations in the chilled water supply temperature, which ranged between 7 and 14 °C (44.6 to 57.2 °F). During this period, there were no manual interventions by facility managers to adjust the temperature settings; control was fully automated based on AI-predicted heat loads. The temperature differential between the chiller supply and return averaged approximately 5.7 °C (42.26 °F), which is nearly double that observed in August 2022. By operating with a larger temperature differential, the flow rate of chilled water was reduced, contributing to a large reduction in power used by the chilled water pump due to the automatic optimal control.

Despite the higher outdoor temperatures, along with a 37.4% increase in manufacturing heat load in 2023, the chiller's energy consumption increased by only about 4.6%. The system coefficient of performance improved from 0.51 to 0.67, thereby demonstrating the efficacy of the automatic optimal control. Table 2 shows the chiller's energy consumption on days with comparable average outdoor temperatures for the 2022 and 2023 periods as an example. On each selected day, the energy consumption in 2023, with automatic optimal control, was lower, achieving a reduction of 13%–16%.

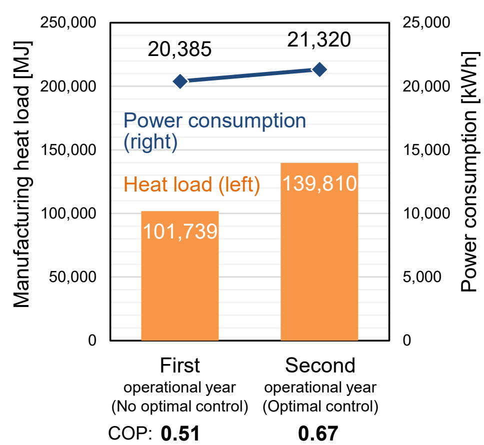

Fig. 7 Manufacturing heat load and energy consumption of chillers

Table 2 Energy consumption of chillers during 2022 and 2023 periods

Day	Average outside air temperature (℃)	AI-driven optimal control	Power consumption (kWh)	Saving rate, 2023/2022 (%)
August 8, 2022	30.6	Off	2,120	87
August 7, 2023	30.6	On	1,840	
August 11, 2022	30.7	Off	2,180	84
August 18, 2023	30.7	On	1,840	
August 15, 2022	29.6	Off	2,000	87
August 11, 2023	29.6	On	1,730	

2.3. Air heat exchange system using seismically isolated pit

The factory has an air heat exchange system that uses a seismically isolated pit. This system is designed to reduce the heat load on the outside air handling units during both summer and winter. The system uses geothermal energy, which has minimal seasonal temperature fluctuations. The temperature and humidity in the seismically isolated pit are monitored continuously. If the conditions in the pit become equivalent to or less beneficial than those of the outside air (e.g., during the rainy or intermediate seasons between summer and winter), the system automatically switches to drawing air from the regular outside intake.

Even during summer with peak outside temperatures reaching 40°C (104°F), the pit temperature stayed around 25°C (77°F). During winter, when outside temperatures dropped to 0°C (32°F), the pit remains at about 15°C (59°F). As a result, the annual heating and cooling load was reduced by approximately 25%.

3. IAQ and Thermal comfort

The ventilation and indoor temperature are managed based on ASHRAE Standard 55 for factories. Air filters were selected following [redacted] standards, with ASHRAE guidelines as a reference. Temperature and humidity sensors and particle counters have been installed throughout the factory to enable continuous environmental monitoring. Although energy-saving operations are conducted by AI-driven automatic optimal control, an interlock control system has been implemented to enable reversion to baseline settings if there is a deviation from the predefined settings.

4. Innovation

The evaluation for net ZEBs under the [redacted] Building Energy Efficiency Act excludes the energy consumption of air conditioning and ventilation systems in factory production areas. These systems account for most energy consumption in a factory and thus their exclusion is a major limitation in the evaluation of ZEBs. To achieve carbon neutrality, a comprehensive energy evaluation framework, ZEF, was developed. This framework includes air conditioning, ventilation, and other systems in the production area.

Developing the ZEF evaluation framework and introducing it to a manufacturing factory is a world first, to the best of our knowledge (Fig. 8). The promotion of technology and initiatives associated with ZEF to the public represents an important advancement for [redacted]'s manufacturing sector. The technologies implemented here are applicable across numerous factories, offering the potential for a major ripple effect from this innovative approach in and beyond [redacted]

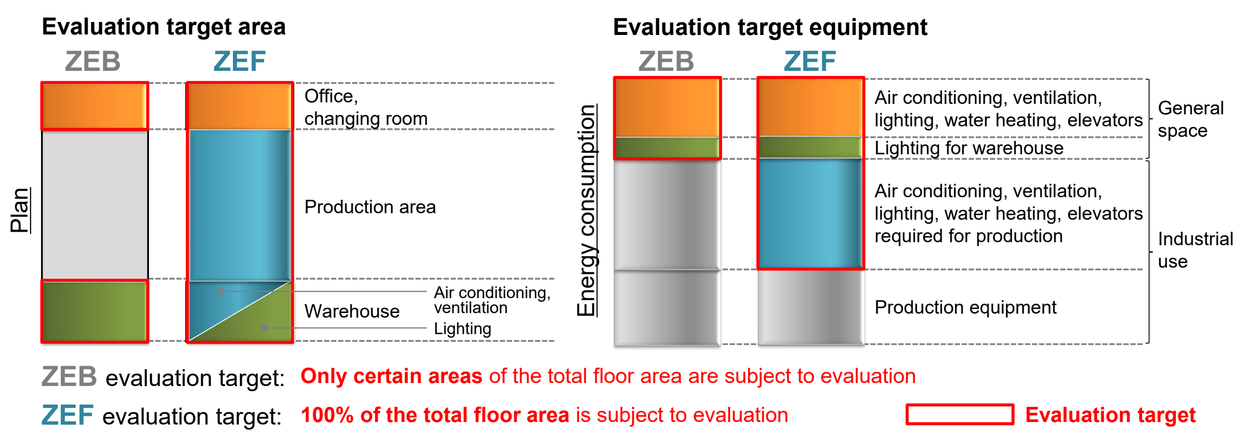

Fig. 8 Concept for the energy evaluation framework for a net ZEF

5. Operation and Maintenance

Energy meters have been installed for each area and piece of equipment, allowing for the convenient display of energy usage data. The building energy management system (BEMS) and digital signage provide an overview of the collected energy data, which are stored in the cloud BEMS. This allows for remote monitoring of the data daily. The data set for the air conditioning systems and associated energy consumption is subjected to continuous analysis by experts from [redacted] Corporation (Fig. 9 (a)). Moreover, a ZEF monitor was developed, enabling [redacted] and all stakeholders to share information in real time, thereby facilitating continuous tuning and operational improvements (Fig. 9 (b)). As a risk countermeasure for cloud implementation, careful consideration is given to data security. [redacted] Corporation operates in accordance with the ISO27001 standard on information security, and has now obtained ISMS27001 certification, as well as additional cloud security certification.

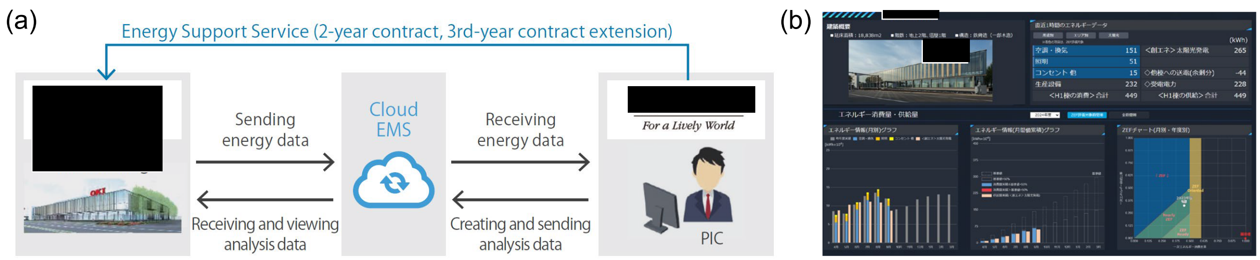

Fig. 9 (a) Remote monitoring energy management system and (b) screenshot of the ZEF monitor

Fig. 10 (a) compares the annual primary energy consumption of the factory in its second operational year (financial year (FY) 2023) with data from a reference factory. The ZEF achieved a 54% reduction in annual operational energy consumption and an additional 40% reduction through solar power generation, resulting in a total reduction of 94%.

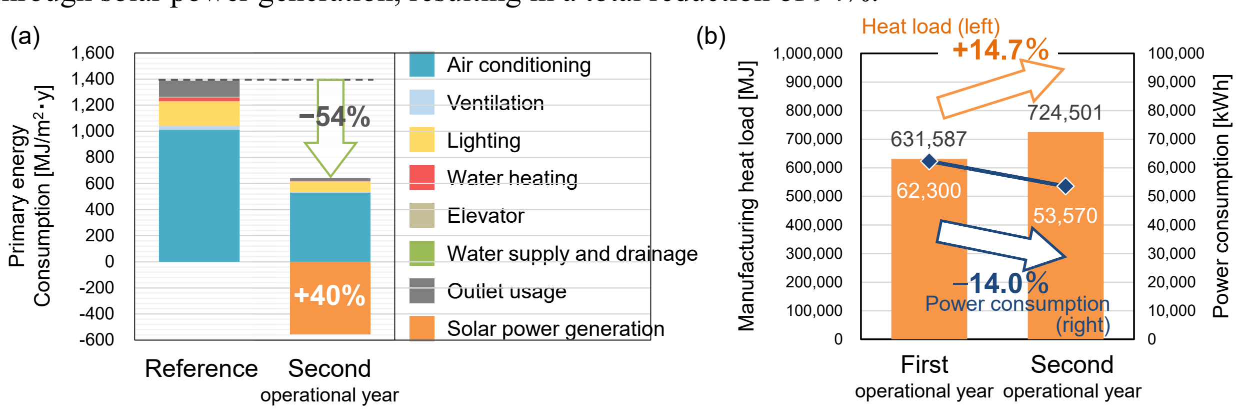

Fig. 10 (a) Annual primary energy consumption and (b) chillers' heat load and power consumption

Fig. 10 (b) shows the manufacturing heat load and power consumption of the chiller in the first operational year (FY2022) and the second (FY2023). In the second year, because of the increase in the average outdoor temperature and manufacturing equipment use, the heat load increased by 14.7%. In contrast, power consumption for chillers decreased by 14% due to AI-driven automated optimal control. Thus, the energy-saving effect on air conditioning systems was confirmed, and efforts continue to reach a net reduction of over 100% to achieve a net ZEF.

6. Cost effectiveness

The baseline energy consumption from building equipment was 28,842 GJ/year (27,316 MBtu/year). In the second year (FY 2023), it was reduced to 13,577 GJ/year (12,859 MBtu/year). This reduction in energy consumption equates to an annual operational cost saving of approximately 273,430 USD. It is estimated that the initial costs associated with the implementation of energy-saving systems will be recouped within approximately 5 years.

7. Environmental impact

In the second year of operation, the CO_2 emissions calculated from the energy consumption of 13,577 GJ/year (12,859 MBtu/year), amounted to 554 tons of CO_2 per year (29.4 kg-CO_2/m^2). Accounting the energy generated by photovoltaic solar cells, net CO_2 emissions were reduced by 412 tons per year (21.9 kg-CO_2/m^2) to 142 tons per year (7.5 kg-CO_2/m^2), approaching net-zero carbon emissions.

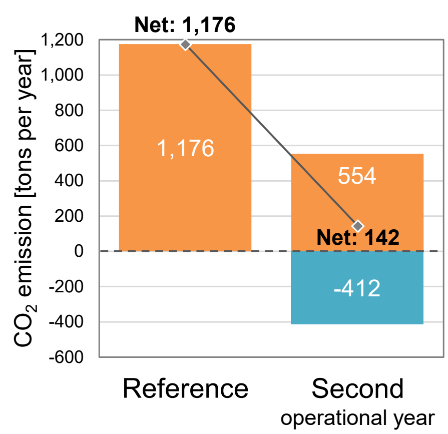

Fig. 11 Annual CO_2 emissions

8. Conclusion

Factories, which are major energy consumers, are pivotal in achieving carbon neutrality by 2050. More companies are committing to carbon neutrality in their supply chains. Failing to meet these commitments could lead to lost business opportunities and impact continuity. In this context, the development of a ZEF evaluation framework, which includes the assessment of factory production areas, could substantially reduce CO_2 emissions from factory operations. This initiative is anticipated to serve as a catalyst, accelerating the path toward achieving carbon neutrality.