Journal of Cleaner Production 516 (2025) 145730

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Demand response measures at a small-scale wastewater treatment plant installed with a photovoltaic system

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ARTICLE INFO

Keywords:
Load shifting
Load adjustment
Energy management
Oxidation ditch
Sludge treatment

ABSTRACT

Wastewater treatment plants (WWTPs) consume large amounts of energy, and measures to upgrade WWTPs to become self-sufficient through the use of renewable energy are being promoted. We developed an electricity demand simulation model of a small-scale WWTP with a photovoltaics (PV) system at a 30-min resolution. A demand response (DR) measure for the plant's wastewater treatment process was designed to match a high-load operation with continuous aeration to the PV daily generation curve by utilizing a load-adjustment tank. Similarly, a DR measure for the plant's sludge treatment process was designed to increase the dehydrator operating time and take advantage of seasonal PV generation surpluses by receiving household sludge waste collected from outside of the sewerage area. Self-sufficiency and self-consumption rates were evaluated based on the electricity supply-demand balance at a 30-min resolution under the condition that the total annual PV power generation and total annual demand of the WWTP were approximately equal. Compared to the base scenario that reproduced the electricity demand in the WWTP in FY2018, self-sufficiency and self-consumption rates were both increased by 14.1 % through implementation of the two DR measures under DR-W+S scenario. The improvement of self-sufficiency also led to a reduction of greenhouse gas emissions, and the annual emissions were reduced by 36.3 % under the DR-W+S scenario compared with the base scenario. From the aspect of economic in the 20-year project period, the estimated net present value was turned to be positive in the 14th year under DR-W+S scenario by improving the electricity trade balance.

1. Introduction

As part of efforts to achieve carbon neutrality by 2050, the sewerage sector is working to reduce energy consumption and greenhouse gas (GHG) emissions. In Japan, the Global Warming Prevention Plan of the Ministry of Land, Infrastructure, Transport and Tourism has set a medium-term target for the sewerage sector to reduce GHG emissions in 2030 by 2080 kt CO_2eq compared to the 2013 level (MLIT, 2022), which can be broken down into a 600 kt CO_2eq reduction through energy savings, a 780 kt CO_2eq reduction in N_2O emissions by upgrading dewatered sludge incinerators to raise the incineration temperature to 850 °C, a 700 kt CO_2eq reduction through the recovery and use of bioenergy from sewage sludge, and additional reductions from the introduction of renewable energies such as photovoltaic (PV), micro-hydroelectric, wind power generation, and use of sewage heat. The Japanese sewerage sector emitted 5221 kt CO_2eq in Fiscal Year (FY) 2015, including the largest 1783 kt CO_2eq (34 %) related to grid electricity consumption for wastewater treatment and the second largest 1021 kt CO_2eq (19 %) caused by N_2O emissions, mainly derived from the incineration of dewatered sludge (Wang and Nakakubo, 2022). Although N_2O emissions are expected to be drastically reduced by introducing energy conversion technologies targeted at dewatered sludge and can be combined with subsidiary fuel consumption reduction (Wang and Nakakubo, 2022), energy savings in the process of biological wastewater treatment must undergo a trade-off with N_2O emissions through aeration control (Abulimiti et al., 2022). Therefore, approaches to reduce electricity consumption or fulfill electricity requirements using renewable energy within the Japanese sewerage sector are

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https://doi.org/10.1016/j.jclepro.2025.145730
Received 27 October 2024; Received in revised form 6 May 2025; Accepted 14 May 2025
Available online 19 May 2025

needed.

In Japan, municipal wastewater is generally treated using processes that fall into three categories in wastewater treatment plants (WWTPs), whose treatment performance characteristics were statistically analyzed by Soda et al. (2013). The conventional activated sludge (CAS) process is mainly implemented in medium- and large-scale municipalities without the need for eutrophication control in seawaters, rivers, lakes, and marshes as discharge destinations. WWTPs requiring eutrophication control adopt modified treatment processes, such as anaerobic–oxic for phosphorus removal, recycled nitrification-denitrification for nitrogen removal, and anaerobic–anoxic–oxic (AAO) for both. The third method is the oxidation ditch (OD) process, which is mainly carried out in small-scale WWTPs. Longer hydraulic retention times (HRTs) (24–48 h) were set in a circular aeration tank with rotary brush aerators compared to those used in CAS processes (6–8 h) (Soda et al., 2013). The operation contributes to accommodating the large daily fluctuations in inflow load that tend to occur at small-scale WWTPs.

While long HRTs ensure stable treatment, they also include induce an amplified oxygen requirement, which leads to an increase in the amount of electricity consumed per unit volume of water treated by the OD process compared with CAS (Mizuta and Shimada, 2010). In Japan, in FY2020, there were 2147 WWTPs nationwide, 1451 (68 %) of which were classified as small-scale WWTPs with a disposal capacity of <10, 000 m^3/d, and of those, 1034 plants used the OD method (JSWA, 2023). Given the large number of WWTPs using the OD process, methods for reducing the specific energy consumption of these plants are needed. The optimization and control strategies of aeration for energy savings, including OD methods, were reviewed by Gu et al. (2023), whereas an energy-saving measure for OD at a practical level in Japan was not covered.

Many technologies for energy recovery from sewage sludge, such as incineration systems with waste-heat power generation and solid fuel conversion systems, cannot be installed in small-scale WWTPs because of high project costs (Wang and Nakakubo, 2021). Even in large-scale municipalities with populations of more than one million, thermal treatment plants have been constructed in one or two core WWTPs to aggregate dewatered sludge from multiple WWTPs in Japan (Wang and Nakakubo, 2022). Thermal treatment and waste-to-energy systems are positioned as technologies for large WWTPs, including a major base for dewatered sludge over a wide area (Gherghel et al., 2019). At a smaller scale, an anaerobic digestion (AD) tank can be installed in middle- and small-scale WWTPs (Scarlat et al., 2018), whereas systems for AD with the effective use of biogas cannot be installed in WWTPs with an inflow water volume of <19,000 m^3/d because the production of biogas is insufficient to meet the plant's power generation needs (Strazzabosco et al., 2019). One potential solution for small-scale WWTPs is the use of a PV system to generate renewable energy. However, it remains to be clarified how PV generation and energy demand can be adjusted to match the PV daily generation curve.

The first step in energy management is to improve specific energy consumption. Cardoso et al. (2021) have summarized the specific energy consumption of WWTPs in several countries, stratifying by treatment level and plant location, and identified the contextual and underlying factors that affect energy performance. Longo et al. (2016) have reported energy-use performance, specific energy consumption per treatment type and plant size, and the factors related to scale that can worsen performance. Chen et al. (2024) have estimated the GHG emission inventory of several sewage treatment systems, including the OD process, and analyzed the correlation among socio-economic indicators, climate indicators, and domestic sewage quantity. The contribution of loading rate control by optimizing aeration volume in a biological aeration tank, and negative specific energy consumption due to the excess processing capacity have been verified.

Data mining and optimization can be utilized to improve specific energy consumption in WWTPs. Asadi et al. (2017) have developed optimization models by using data mining algorithms and shown the effectiveness of the models to minimize treatment process dissolved oxygen (DO) and energy consumption without sacrificing water quality. Ye et al. (2024) have developed multiple linear models for the prediction of the effluent biochemical oxygen demand (BOD) and unit energy consumption of WWTPs and have reproduced recorded values for different scale WWTPs. Determination of current energy consumption at high time-resolution and its verification are necessary to estimate the effectiveness of energy saving and demand response (DR) measures. Shinchi WWTP (Shinchi Town, Fukushima Prefecture, Japan) is examined in the present study, for which the electricity consumption at each stage of the water treatment process was recorded at 30-min resolution (Maki et al., 2019).

Systems for upgrading WWTPs to become 100 % self-sufficient by the use of renewable energy are being developed. One promising approach is the use of AD with biogas recovery. Gu et al. (2017) have examined energy efficiency optimization through a combination of energy saving and energy recovery to improve the energy self-sufficiency of WWTPs through the use of biogas produced by AD and a power generator. Bustamante and Liao (2017) reported a self-sustaining and high-strength wastewater treatment system involving AD and aerobic treatment, and solar and biogas energy are used to support the treatment process. Liu et al. (2021) have proposed a net-zero energy wastewater treatment model and optimal pathways that combine AD with heat and power generators, PV, and heat pumps connected to sewage heat. However, for a small-scale WWTP, AD cannot be used and energy storage devices such as batteries are not an option due to initial investment constraints. We covered a simple solar PV self-sufficiency system.

Modeling the balance of electricity supply and demand at WWTPs with PV system requires an understanding of seasonal and temporal variations. Colacicco and Zacchei (2020) have reported an estimation method to maximize the self-consumptions of aeration blowers installed in the oxidation tanks of WWTPs in light of seasonality, which effects the oxygen solubility in the tanks, and the method can be used to design the peak power of a PV plant according to monthly energy supply-demand balances. Donald et al. (2023) developed a 24-h, 365-day simulation model with a control algorithm to manage electricity supply from a solar PV system to an electrolyzer installed in a WWTP, and to determine grid electricity import and export, while ensuring the system maintained a reliable supply of hydrogen to meet the specified daily offtake scenario. Our study deals with the seasonal variability of oxygen requirements, mainly caused by decreases of oxygen solubility due to higher water temperatures in the summer, by controlling the oxygen supply in the aeration system of the OD process. In addition, we prepared a simulation model that can estimate the supply-demand balance of electricity at a 30-min resolution for load shifting to the time of PV generation.

Relevant research dealing with DR at WWTPs can be categorized as measures to improve self-sufficiency for renewable energy and measures to consume electricity during less expensive grid electricity rate hours. To respond to the Spanish energy tariff structure, Aymerich et al. (2015) analyzed three aeration control strategies based on DO and total ammonia for a reduction of total energy costs. Focusing on lower late-night electricity prices, Simon-Várhelyi et al. (2020) have proposed the partial storage of influent wastewater during the day and the treatment of the stored wastewater during the night, and reported the best time scheduling in terms of total operation cost and effluent quality. Musabandesu and Loge (2021) reviewed previous researches analyzing the energetic flexibility in wastewater treatment process, and then estimated the effectiveness of DR measures that includes one diverting flow equalization basins. Based on existing measures to control the operating hours of each process, robust load shifting of aeration in the wastewater treatment process can be achieved by introducing influent load adjustment tank and control for oxygen requirements.

The present study investigated energy management at a small-scale WWTP assumed to be equipped with a large PV system and utilizing a novel OD process with aeration control for oxygen requirements. The purpose of the study was to evaluate the effectiveness of DR measures in enhancing electricity self-sufficiency of small-scale WWTPs by scheduling electricity consumption in line with periods of high PV electricity generation. Two types of DR measures were considered: load shifting of the aerator load rate in the wastewater treatment process and scheduling the operation of the dehydrator in the sludge treatment process. The temporal coincidence to PV generation time period by introducing DR measures in the target WWTP was evaluated by determining self-sufficiency and self-consumption rates based on the supply-demand balance of electricity at a 30-min resolution. The self-sufficiency rate indicates how much of the electricity demand can be covered by the onsite PV output. The self-consumption rate indicates how much PV output is consumed by the WWTP. In addition, GHG emissions and project cost were used as complementary indicators under the condition that the WWTP was connected to the power grid under a feed-in-tariff (FIT).

2. Materials and methods

To examine the effectiveness of DR measures based on the supply-demand balance between the PV power output and the demand of the WWTP, we constructed an electricity demand simulation model whose framework is shown in Fig. 1. This study reproduced the output value of the standard oxygen requirement (SOR) via aeration and quantified the discrepancy between the theoretical values of two types of OD processes. The electricity demand simulation model with a 30-min resolution can examine load shifting in aeration operations through SOR estimation. The scheduling of electricity consumption for the PV power generation curve, analyzed by Shao et al. (2024), covered aeration operation in the AAO process and focused on three different weather conditions (sunny, cloudy, and rainy days) in September as a case study. Our simulation considered load shift control applied to a novel OD process. Its effectiveness was evaluated throughout the year, focusing on seasonal variations in the SOR that notably occur in small-scale WWTPs.

2.1. Target small-scale WWTP and energy consumption monitoring

We consider the case of Shinchi WWTP, located in Shinchi Town, in the northeastern part of Fukushima Prefecture, Japan. The WWTP was severely damaged by the 2011 Tohoku Earthquake and was reconstructed. The plant possesses two OD tanks, each with a disposal capacity of 1303 m^3/d, but only one tank is in constant use in light of daily inflow (average 873 m^3/day in FY2018). The treatment process is as follows: biological reaction tank (OD process), final sedimentation basin, and disinfection for wastewater treatment; thickening and dewatering for sludge treatment; intermediary station for pumping up influent; and ancillary facilities for management and operation. The plant does not have a primary sedimentation basin, which is not unusual for small-scale WWTPs using the OD method in Japan. Dewatered sludge is recycled outside the plant.

To understand the plant's energy consumption at a high time-resolution, we installed a real-time electricity monitoring system at the plant and the electricity demand of each process was recorded. Maki et al. (2019) have reported a Markov switching-based hourly electricity consumption prediction model. The operation patterns of major equipment are reproduced, and the operation schedules can be determined from both the monitoring values and the prediction model. In the present study, we developed an electricity demand simulation model linked with the operation schedule of each process at a 30-min resolution. The monitoring of electricity consumption was conducted in FY2018. Operational records containing data related to influent, effluent, and control of the OD process for FY2018 were provided by Shinchi WWTP.

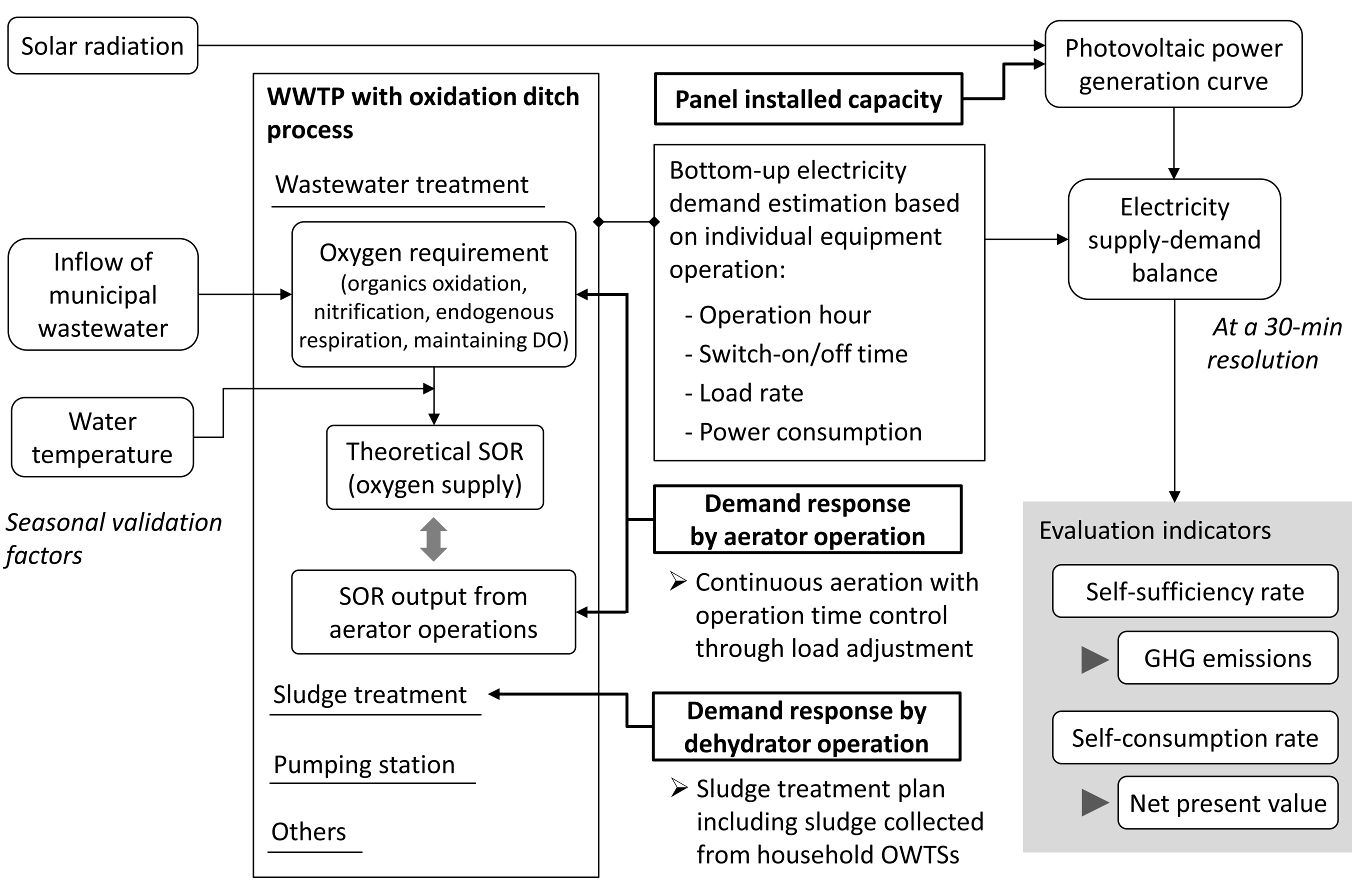


Fig. 1. Framework of our electricity demand simulation model constructed for the estimation of energy demand and analysis of the electricity supply-demand balance.

2.2. Scenarios and DR measures

Four scenarios were examined as shown in Table 1: base, Save Energy (Save-E), Demand Response for the Wastewater treatment process (DR-W), and Demand Response for Wastewater and Sludge treatment processes (DR-W+S).

The base scenario is the actual plant operation conditions in FY2018, and the OD tank change between aerobic and anoxic depending on the time of day; aeration is performed by timer control for intermittent aeration. The tendency of increased electricity consumption per unit volume of water treated in a small-scale WWTP was reproduced in terms of the actual oxygen requirement (AOR) and SOR. The AOR tends to be higher because it operates at higher mixed liquor suspended solid (MLSS) concentrations to maintain lower BOD-MLSS loadings against large variations in daily inflow. The output SOR, defined as the operation performance of the aerator, tends not to be in line with the theoretical SOR owing to the operation with a margin of error, such that the oxygen supply rate remains sufficient even under sudden increases in the inflow load.

In the Save-E scenario, energy savings are pursued by introducing a dual DO control system to the OD process (see Nakamachi et al. (2012) for details) to address over-oxygenation against inflow fluctuations in the base scenario. The OD tank is equipped with a vertical axis flow generator, membrane diffusers, and blowers so that the flow generator maintains the activated sludge in suspension and drives the wastewater around the circular channel. Aerobic and anoxic conditions are spatially formed in the biological reaction tank and continuous aeration is introduced. Optimization of the oxygen supply to the aerobic zone is conducted automatically based on the DO concentrations measured in real time immediately downstream of the diffuser (DO probe 1) and at the end of the aerobic zone (DO probe 2). The aeration and water flow generator load rates are adjusted independently based on the optimization. While automatic DO control systems using older sensors and probes incur costs due to their high-frequency maintenance, the dual DO control system adopts a fluorescent DO meter to address this issue. The aeration controls, according to the theoretical SOR in response to daily and seasonal influent variations, not only contribute to reducing excessive oxygen supply but also decrease the AOR by increasing the BOD-MLSS load and lowering the oxygen requirement for endogenous respiration by activated sludge. A similar approach for the OD tank, an automatic remote-control system using DO and Oxidation-Reduction Potential (ORP) probes, was demonstrated by Vega et al. (2013), and the power levels of the blower are switched according to those measurements to form the appropriate aerobic zone.

In the DR-W scenario, in addition to introducing the dual DO control system, the plant's unused biological reaction tank is used for influent load adjustment, such that aeration can be conducted during the daytime to coincide with PV power generation. The influent ratio is an indicator of the excess possessing capacity, defined as the ratio of the average daily wastewater inflow on a sunny day to the processing disposal capacity of the installed tanks. There are 629 small-scale WWTPs in Japan with two or more OD tanks, of which 378 have an influent ratio of <0.50 (Table S1). The target WWTP also has an influent ratio of <0.50, indicating that only one tank is required for wastewater treatment, whereas the excess tank can be used for influent load adjustment. The effectiveness of the load equalization tank in maintaining a constant load to an aeration tank was confirmed in the San Luis Rey WWTP, California, as a trial for automated DR for wastewater treatment, even though the blowers were not equipped with variable frequency drives (VFDs) (Thompson et al., 2010). Scheduling of electricity consumption for the power generation curve, Shao et al. (2024) set the operating conditions of its two high-speed suspended centrifugal blowers with VFDs in the AAO process, and the load rate of each blower was simulated based on three types: off, the minimum volume of air when the blower was turned on, and the maximum volume of air. In the simulation of the DR-W scenario, two units of aerators with VFDs were operated in the novel OD process based on the estimates of the theoretical SOR applied to inflow adjustment.

In the DR-W+S scenario, in addition to introducing the dual DO control system and the DR measure for the water treatment process, the number of days the plant receives sludge is also increased and the dewatering equipment is operated during periods of PV power generation. In Shinchi Town, 3452 individuals live in housing connected via a sewage system to the WWTP, and 3634 individuals live outside the sewage area and use an onsite wastewater treatment system (OWTS). Under the Japanese municipal solid waste (MSW) management system provided by the local government, OWTS sludge is treated as household waste, and a night soil disposal plant treats night soil and OWTS sludge after collection by sludge trucks. An integration measure using a WWTP with an AD tank to receive OWTS sludge and increase biogas production has generally been promoted in Japan (see Suzuki et al. (2017) as one of the leading-edge projects), whereas receiving OWTS sludge using a WWTP as a part of the DR measure can also be proposed for sludge treatment functional integration. In this scenario, it was assumed that the plant would accept sludge from each household's OWTS once per year, and the collected OWTS sludge would be stored in the tank and treated intensively for months with large PV power surpluses considering seasonality.

2.3. Electricity demand simulation model

2.3.1. Bottom-up demand estimation model

Electricity demand in the target WWTP was simulated by reproducing the plant's operation schedule at 30-min resolution by multiplying switch-on/off time (hour), load rate (%), and power consumption (W) for each process. Table S2 shows the technical specifications of the

Table 1
Summaries of the four scenarios examined in the present study.

Scenario	Demand response measures implemented	Summary
Base scenario	None. Reproduction of actual operations at the Shinchi WWTP in Fiscal Year (2018).	Aeration system: Operated with a mixed liquor suspended solids (MLSS) concentration of 4000–6500 mg/L to control for low biochemical oxygen demand (BOD)-MLSS loads. The conditions in the oxidation ditch (OD) tank can be aerobic or anaerobic depending on the time of day, repeating 16 times for 90 min at equal intervals under intermittent aeration conditions.
Save-E	Advanced aeration control	(i) A dual dissolved oxygen (DO) control system, one of the aeration control methods, is assumed to have been installed. The MLSS concentration is set at around 3000 mg/L with a BOD-MLSS load of 0.04–0.06 (kg BOD/kg MLSS/d). An aerobic zone and an anaerobic zone were formed in the OD tank and the loading rates of the aerators and water flow generator are operated based on oxygen requirements followed for daily fluctuations in inflow load.
DR-W	• Advanced aeration control • Demand response (DR) measure implemented for wastewater treatment	(i) + (ii) The unused reaction tank is used as a load-adjustment tank for the dual DO control system. Aeration is conducted during the day to coincide with photovoltaic (PV) power generation.
DR-W+S	• Advanced aeration control • DR for wastewater treatment • DR measure for sludge treatment	(i) + (ii) + (iii) Sludge from onsite wastewater treatment systems is received from outside the sewerage area. Dewatering equipment is operated during the day to coincide with PV power generation.

equipment installed at the time of the study, and Table S3 and S4 show the operation settings used for the aeration equipment and the other equipment, respectively, under the base scenario. The operation manager determines the ratio of high-load time to low-load time at 90-min interval and intermittent aeration is not controlled in real-time under the base scenario.

The formulae used to estimate AOR and the settings of the related parameters are listed in Table S5 and S6, respectively, and those for SOR are summarized in Table S7 and S8, respectively. Daily influent, BOD, suspended solids (SS), and total nitrogen (T-N) loads were estimated based on the daily values recorded at the target WWTP in FY2018 (Fig. S1 and S2). Theoretical SOR values were estimated using the water temperatures measured in the OD tank at the target WWTP (Fig. S3), and the excess electricity consumption in the OD process can be analyzed by comparing the theoretical and actual output values of SOR.

2.3.2. Estimation of oxygen supply and its saving by dual DO control

The MLSS concentration was set at around 3000 mg/L with a BOD-MLSS load of 0.04–0.06 (kg BOD/kg MLSS/d) by automatic load rate control in real time for the OD process with dual DO control (Fig. S4). The inflow monitoring values were obtained on a daily basis (m^3/d) and then the inflow (m^3/30 min) was allocated from the reproduced operation records of the intermediary pumping station that pumps the inflow water. A simple estimation model of AOR in 30-min time segments according to the daily variation was constructed for the Save-E scenario (Table S9 and S10). The two units of aerator with VFDs (25.6 kg-O_2/h, 15 kW of power consumption, minimum of one unit operating at 50 % load rate) were assumed to operate every 30 min with load rates ranging from 25 % to 100 % (set in 5 % increments). The water flow generators (3.70 kW, 2 units) were assumed to operate independently of the aerators, and the load rates every 30 min were determined.

2.3.3. Load shifting of the oxygen supply in the OD system with dual DO control

Under conditions that met the estimated SOR, the center point of continuous aeration at a high load rate was placed from 11:30 to 12:00, which is the south-central time of Fukushima Prefecture throughout the year (Table S11). The seasonality of increasing high load operation time from the beginning of July to the end of September tends to coincide with the seasonality of PV output.

2.3.4. Receipt of sludge from OWTSs

Dehydrator load shifting was conducted depending on the amount of sludge treated under the DR-W+S scenario (Table S12 and S13). The sludge treatment plan is summarized in Table S14. The introduction of the OD process with dual DO control would increase the amount of excess sludge generated, because decreasing the MLSS concentration. The number of days the dehydrator was operated was not changed, but the daily operating hours were increased under the Save-E and DR-W scenarios compared to the base scenario in response to the increase. Under the DR-W+S scenario, both the number of operating days per month and the operating hours were increased accordingly. Seasonality was accounted for by setting the amount of sludge received from April to August as high, but limiting the amount received from September to February to 50 t wet per month, considering the monthly PV power surplus under the DR-W scenario as a reference. In particular, higher running of dehydrator during May and June is effective to use PV power surplus when SOR estimates are low.

2.4. Evaluating effectiveness of DR measures

2.4.1. Self-sufficiency and self-consumption rates

The supply-demand balance was analyzed, assuming that a large-scale PV system without storage batteries was installed at the target WWTP. Power generation by the PV system at a 30-min resolution was estimated using the equations and parameters shown in Table S15 and S16. Fig. S5 shows the daily aggregated power generation for a 1000 m^2 PV panel installation in FY2018 in the area of the target WWTP and these values were used as reference value per installed area. The PV panel installation area was set such that the total annual PV power generation and the total annual electricity demand of the WWTP were approximately equal. These values were 6300 m^2 under the base scenario, 5700 m^2 under the Save-E scenario, 5400 m^2 under the DR-W scenario, and 5600 m^2 under the DR-W+S scenario. Under the condition that the supply-demand balance was consistent on a total annual quantity basis, self-sufficiency rate (*SSR*; Eq. (1)) and self-consumption rate (*SCR*; Eq. (2)) were determined based on the supply-demand balance:

$$SSR = \sum_t \frac{EC_{PV,t}}{EC_{PV,t} + EC_{Grid,t}} \quad (1)$$

$$SCR = \sum_t \frac{EC_{PV,t}}{EC_{PV,t} + EE_{PV,t}} \quad (2)$$

where $EC_{PV,t}$ (kWh/30 min) is the electricity supplied directly from the PV and consumed by the WWTP, $EC_{Grid,t}$ (kWh/30 min) is the electricity imported from the utility grid under a PV generation shortage and consumed by the WWTP, and $EE_{PV,t}$ (kWh/30 min) is the electricity exported to the utility grid under a PV generation surplus; t is time, and the two rates were aggregated on a daily, monthly, and yearly basis.

2.4.2. Estimation of GHG emissions based on self-sufficiency

The system boundary considered here covers only the processes in the WWTP (Table S2), including the accounts of non-energy origin GHG; direct CH_4 and N_2O emissions from wastewater treatment, sludge thickening, and dewatering; or direct N_2O emissions derived from natural decomposition of nitrogen included in discharged water. The applied CO_2, CH_4, and N_2O emission factors are listed in Table S17.

Assuming self-sufficiency was achieved at the WWTP by using renewable energy, CO_2 emissions were evaluated based on *SSR* by focusing on whether the electricity load of the WWTP could be met by the PV output. Eq. (3) was used to estimate the CO_2 emissions associated with the consumption of grid electricity ($E_{co_2}^{grid}$):

$$E_{co_2}^{grid} = EC_{total} \times (1 - SSR) \times GEF \quad (3)$$

where EC_{total} (kWh/year) is the total electricity consumption by the WWTP, and *GEF* (kg CO_2/kWh) is the CO_2 emission factor of grid electricity. The OD process with dual DO control allows for energy savings without decreasing treated water quality, and a high nitrogen removal rate performance has been achieved (Chen et al., 2012). In the Japanese GHG inventory, the OD method is subject to the same N_2O emission factor as the CAS method (142.0 mg N_2O/m^3), but a lower emission factor (11.7 mg N_2O/m^3) can be used for treatment methods where stable nitrification and denitrification reactions occur (GIO, 2023). In the present study, the lower emission factor was applied to the novel OD method for the following reasons. The N_2O production pathway has been shown to involve hydroxylamine oxidation by ammonia-oxidizing bacteria, nitrifier denitrification by ammonia-oxidizing bacteria, and heterotrophic denitrification by heterotrophic denitrifiers (Ni and Yuan, 2015). An appropriate oxygen supply to match the ammonia nitrogen load and promotion of N_2O reduction by creating appropriate anoxic zones are required to control N_2O emissions, and these requirements can be met by aerating in accordance with the temporal variations in influent load. In contrast, in the conventional OD process, intermittent aeration causes a mismatch between influent load fluctuations and high load aeration, which may increase the N_2O emission rate and induce ammonia overload shock (Zheng et al., 2021).

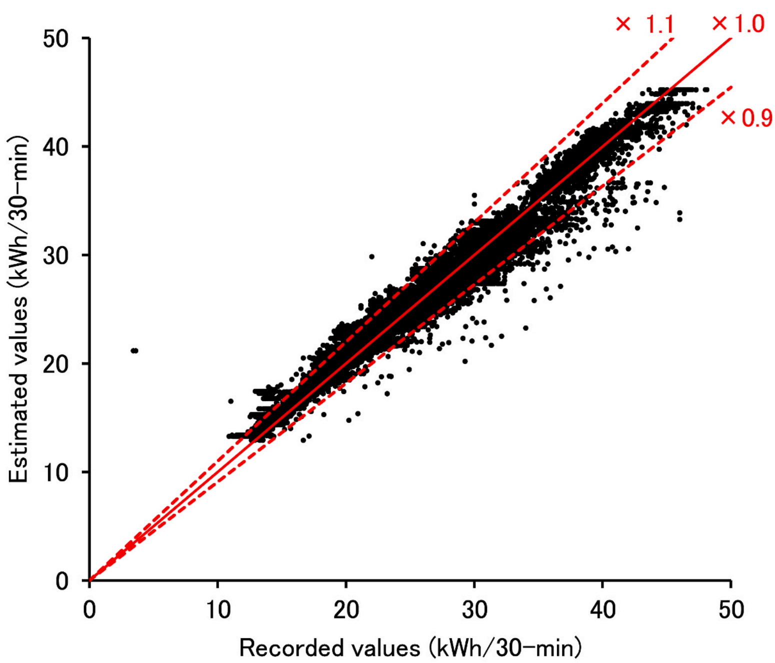
2.4.3. Project cost

Costs and benefits were calculated on an annual basis and were evaluated based on net present value (NPV; Eq. (4)), which was aggregated over a 20-year period:

$$NPV = \sum_t \frac{B_t}{(1+r)^{t-1}} - \left(IC + \sum_t \frac{C_t}{(1+r)^{t-1}} \right) \quad (4)$$

where B_t is benefit from costs avoided due to project implementation at time t, IC is initial (investment) cost, C_t is running cost, and r is discount rate. A discount rate of 3 % was applied with reference to the renewable energy project of Kobashi et al. (2022). Table S18 shows the parameters used to estimate project cost. A With-Without analysis was adopted to estimate benefit, and the condition under which the project does not take place was that the entire electricity consumption by the WWTP will be covered by grid electricity under the base scenario. The unit price of selling surplus PV-derived electricity to the grid is lower than that of purchasing from the grid, meaning that improving the self-consumption rate by implementation of DR measures contributes to reducing running costs.

(a)



(b)

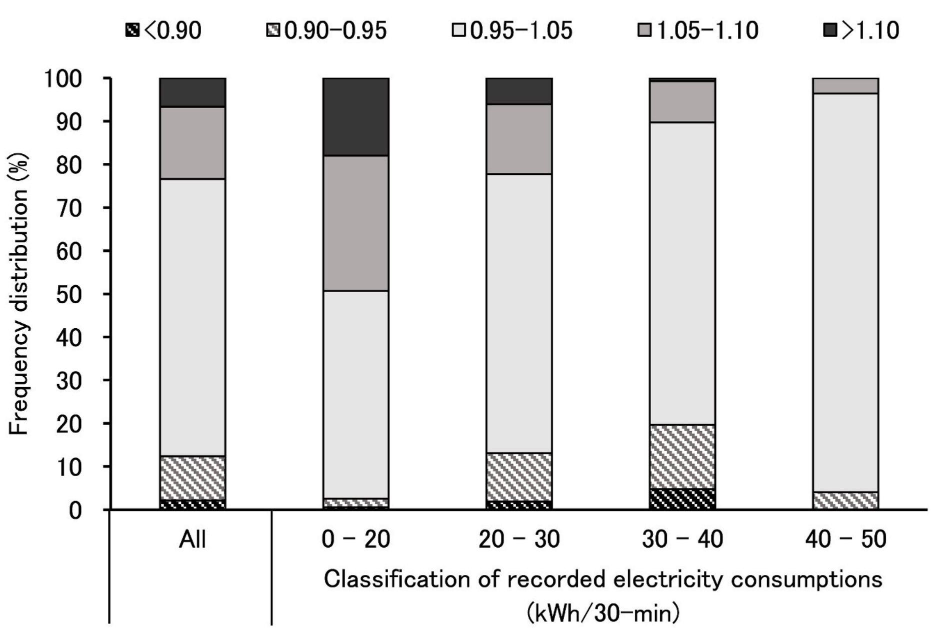


Fig. 2. Model validation for electricity consumption under the base scenario. (a) Comparison between 17,520 estimated and recorded electricity consumption values recorded at a 30-min time resolution for 365 days in FY2018. The central red line indicates a ratio of estimated value to recorded value of 1.0. (b) Frequency distribution of the ratios of estimated value to recorded value.

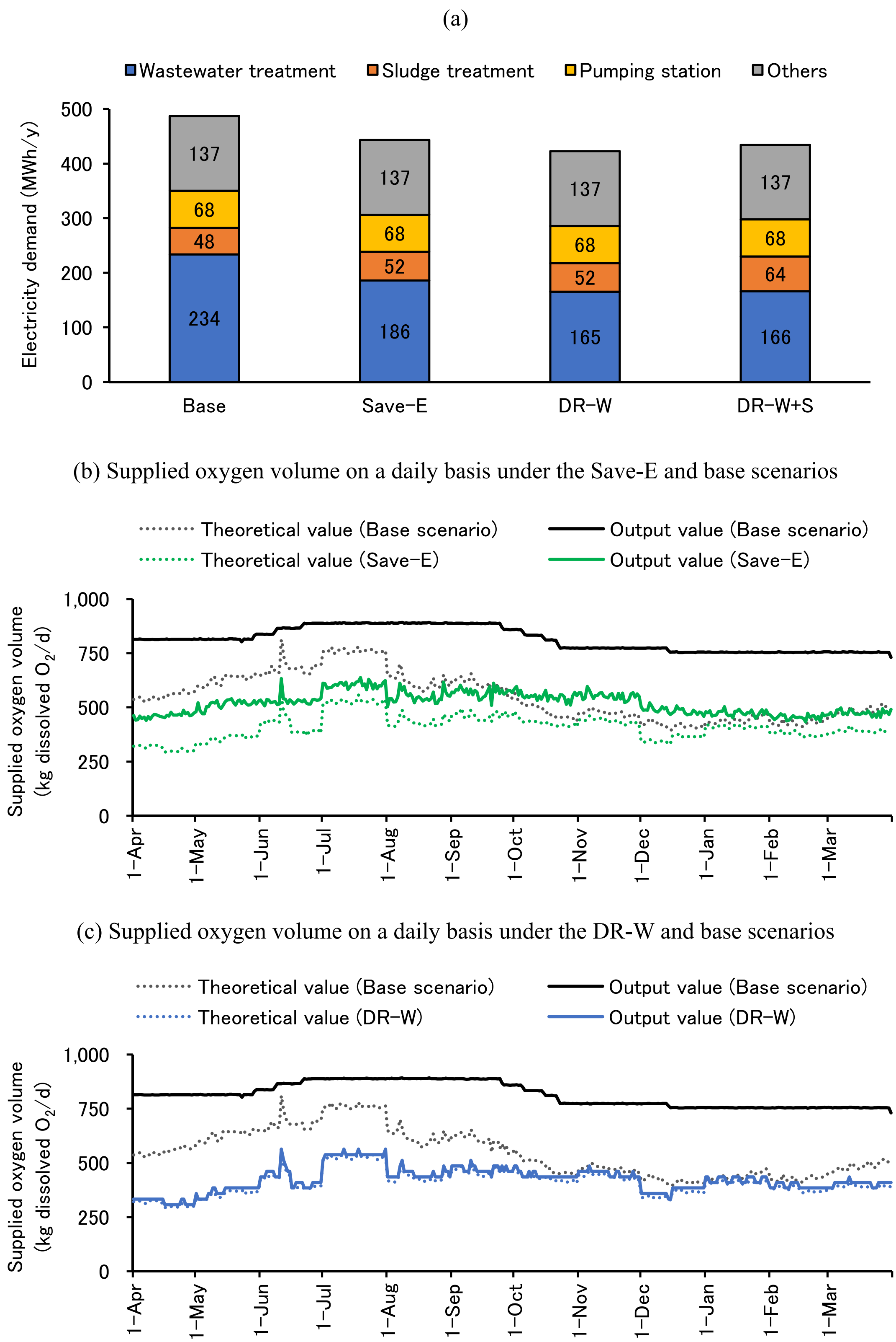


Fig. 3. Estimated electricity demand and savings. (a) Annual aggregated electricity demand for all processes in the wastewater treatment plant. (b) and (c) Daily oxygen supplied to the oxidation ditch tank under the indicated scenarios. Theoretical values are the amount of oxygen supplied based on the estimation of AOR and SOR. Output values are the amount supplied based on the operation of the aeration equipment.

3. Results

3.1. Validation of electricity consumption estimations and energy savings

The accuracy of the model under the base scenario was verified by comparing the estimated and recorded electricity consumption values over a period of 365 days (see examples in Fig. S6). When the estimated and recorded values were plotted and the ratio of each estimated value to the recorded value was determined, 91 % of the values fell within ±10 % of a ratio of 1.0 (Fig. 2a). When the ratios were classified by magnitude of electricity consumption, overestimation occurred more often for values in the 0–20 kWh/30 min category. This is possibly because, while it is easy to set the operating hours of equipment with large power consumptions in accordance with actual power

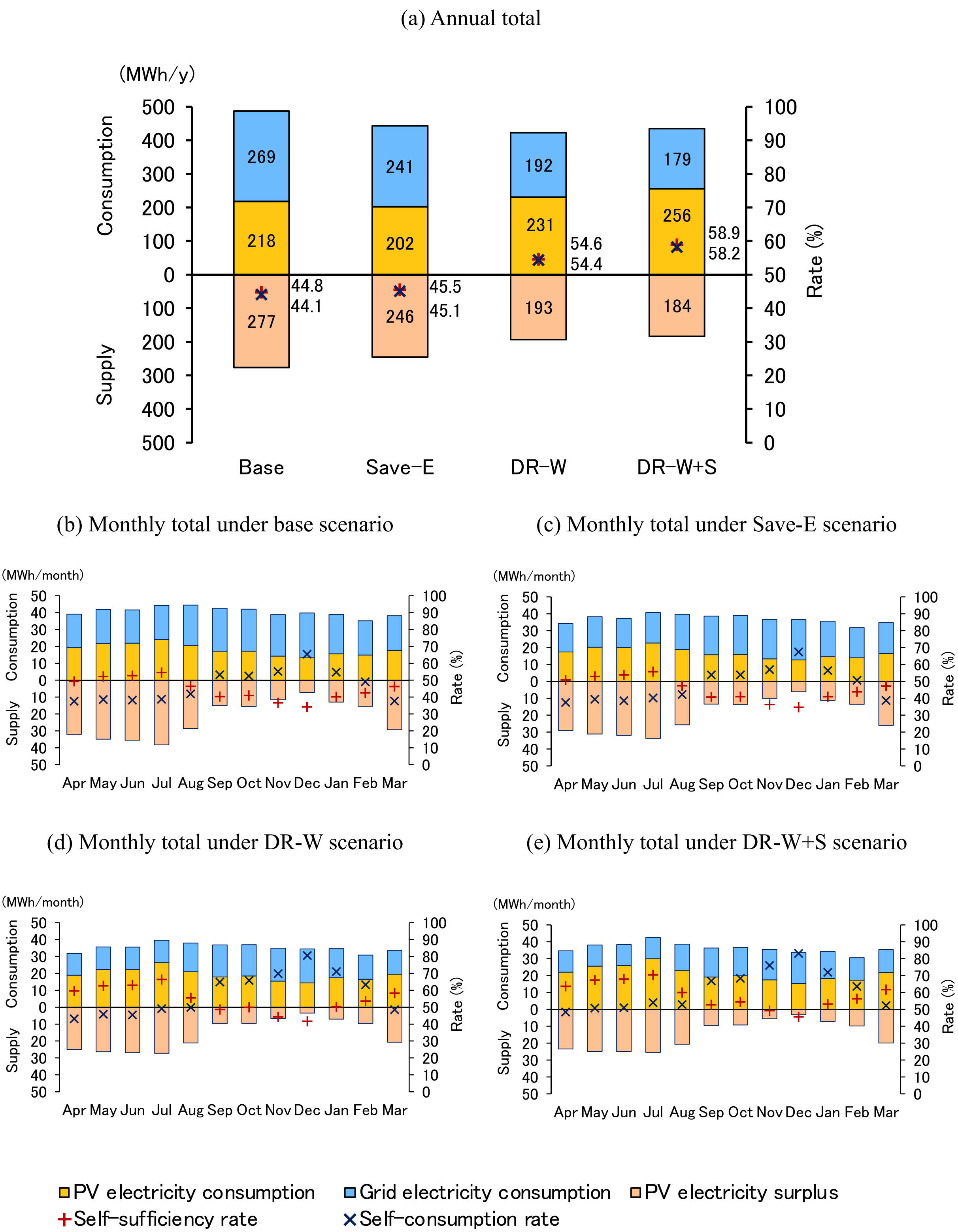


Fig. 4. Estimated electricity supply-demand balances and self-sufficiency and self-consumption rates.

consumption, there is a limit to reproducing the operating hours of equipment with small power consumptions, and the error is reflected in the accuracy. Overall, the operating schedules of equipment with high power consumptions were reproduced with higher accuracy than those with lower power consumptions. The aim was to analyze the effectiveness of energy saving for system conversion from intermittent aeration at equal intervals, and the high repeatability of the intermittent aeration system sequence under the base scenario was confirmed.

The energy savings achieved by upgrading the OD process are shown in Fig. 3. The annual aggregated electricity demand for the total wastewater treatment process was reduced by 21 % under the Save-E scenario and by 29 % under the DR-W scenario compared with that under the base scenario (Fig. 3a). To investigate the cause of this reduction, we plotted the theoretical values of the SOR against the output values for the base, Save-E, and DR-W scenarios (Fig. 3b and c). Under the base scenario, the oxygen supply throughout the year was excessive because the high MLSS concentrations and high-load operating hours were determined by considering the maximum daily variation in the influent load. A 21 % reduction was achieved by introducing automated aeration control against daily fluctuations in inflow load under the Save-E scenario by solving the two problems. Regarding technical adequacy, the same level of savings (19 %) was reported with automatic aeration control in an OD tank with an average inflow of 759 m^3/day (Vega et al., 2013). Under the DR-W scenario, the theoretical and output SOR values were well matched, as shown in Fig. 3c, by consolidating the time of high-load operation at a 100 % load rate of aeration through inflow load adjustment and conversely having the time to turn off. The annual average specific energy consumption of the wastewater treatment process in the DR-W scenario was 0.519 kWh/m^3 compared to 0.733 kWh/m^3 in the base scenario. These savings represent an example of treating the high intensity caused by the mismatching between actual and design inflows to the aeration tank (Torregrossa et al., 2019).

3.2. Evaluation of supply-demand balance

The effectiveness of the DR measures was evaluated by determining the supply-demand balance at a 30-min resolution (see Fig. S7–10 for seasonal examples). The self-sufficiency and consumption rates were evaluated based on the PV electricity consumption and surplus electricity aggregated over the year (Fig. 4a). The self-sufficiency and consumption rates converged to approximately the same values for each PV panel installation setting condition. The self-sufficiency rate increased to 54.6 % under the DR-W scenario and 58.9 % under the DR-W+S scenario, compared with 44.8 % under the base scenario. The period of electricity consumption by automatic aeration corresponding to the daily inflow fluctuations did not match the periods of the PV generation curve throughout the year (see Fig. S11a, two daily rates under the Save-E scenario), and aeration scheduling through daily inflow load control was functional (see Fig. S11b under the DR-W scenario). The effectiveness of scheduling the load rate of the two blowers, including the time to turn off, was also clarified by Shao et al. (2024), whereas manipulable load shifting per unit of time (30-min) in the DR-W scenario is 0–15 kWh. The self-consumption rate through the reduction of the PV power surplus improved from September to February, with a relatively low PV output per 30 min.

According to the results under the DR-W scenario, aggregated on a monthly basis (Fig. 4d), the self-sufficiency rate in July was the highest at 66 % because of the positive correlation between high PV generation (solar radiation) and high aeration operating hours (water temperature), which is an important correlation also analyzed by Colacicco and Zacchei (2020). However, there is a trade-off between self-sufficiency and consumption rates in terms of the seasonality of PV generation. The self-sufficiency rates tended to be higher from April to August; conversely, self-consumption rates were lower during that period (Fig. 4d). The DR-W+S scenario was designed to reduce the PV power surplus from April to July in the DR-W scenario, contributing to an improvement of approximately 5 % in the self-consumption rate for each month (Fig. 4c and d).

3.3. Evaluation by complementary indicators

Table 2 presents the estimated GHG emissions for each scenario. Under the Save-E scenario, a marked reduction in N_2O emissions resulted in a 16.1 % reduction in total annual GHG emissions compared to the base scenario. Similarly, the total annual GHG emissions were reduced by 32.0 % under the DR-W scenario and 36.3 % under the DR-W+S scenario compared to the base scenario. The improvement in the self-sufficiency rate through the DR measures contributed to an additional reduction of 24.1 kt CO_2eq under the DR-W scenario and 30.6 kt CO_2eq under the DR-W+S scenario compared with that under the Save-E scenario. The CO_2 emissions from electricity consumption were the largest, and both energy-saving and DR measures contributed. Based on the PV panel installation conditions for each scenario, grid electricity consumption and resulting CO_2 emissions can be reduced to zero, assuming that the storage batteries are installed with sufficient capacity. Meanwhile, the PV electricity surplus can be used outside the WWTP. The reduction effect will depend on future trends in the acceptance of uncontrolled reverse power flow into a utility grid under local-scale supply-demand balance management.

The estimated project costs based on NPV are shown in Fig. 5. Energy savings led to a reduction in the initial investment in PV panels. Mainly due to a smaller initial investment, the estimated NPV under the Save-E scenario was 13 million Japanese yen, compared to 4 million Japanese yen under the base scenario. A higher self-sufficiency rate led to less electricity imported from the grid but a higher per-unit cost, whereas a higher self-consumption rate led to the export of surplus electricity but a low unit cost, which improved the cost of electricity trade. The DR measures led to an improvement in the electricity trade balance, with the NPV turning positive in the 14th year under the DR-W and DR-W+S scenarios, compared to the 17th year under the Save-E scenario. Thus, the DR measures shortened the period leading to profitability.

In Japan, an FIT system came into effect after a revision in 2017, which reduced the export price of PV electricity; accordingly, it is now lower than the unit price of grid electricity. Compared to the DR-W scenario, the annual total electricity demand increased under the DR-W+S scenario due to receiving and treating sludge from OWTS. Nevertheless, the estimated NPVs of both scenarios were almost identical (Fig. 5), although the initial investment in the PV system increased. In addition to load shifting, increasing the electricity demand by receiving sludge from the OWTS and then utilizing the PV power surplus is also effective from an economic perspective, and the self-consumption rate can be used as an index to evaluate its effective use.

3.4. Response to the installation of PV capacity

The changes in the self-sufficiency and self-consumption rates in response to installed PV capacity are shown in Fig. 6. The increase in self-sufficiency rate with increasing PV capacity will converge at a certain value even when DR measures are implemented, and will not reach 100 % without energy storage systems. Similarly, an increase in PV capacity will lead to a decrease of self-consumption rate. The consumption rate under the Save-E scenario tended to be slightly lower than

Table 2
Estimated greenhouse gas (GHG) emissions.

	Base	Save-E	DR-W	DR-W+S
Total GHG emissions (t CO_2eq/year)	151.9	127.4	103.3	96.8
CO_2	131.2	117.8	93.7	87.2
CH_4	7.8	7.8	7.8	7.8
N_2O	12.9	1.8	1.8	1.8

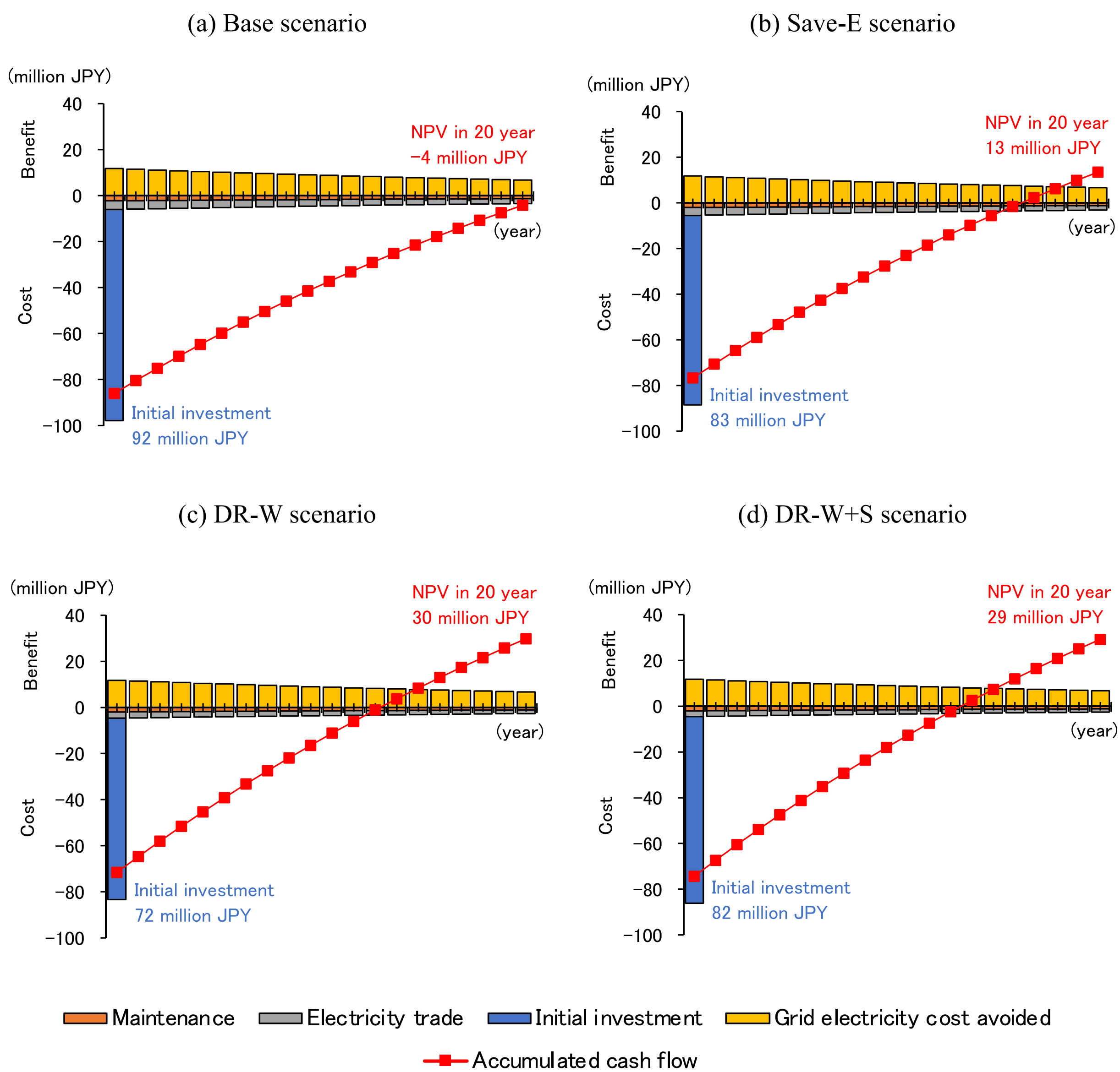


Fig. 5. Estimated project costs based on net present value (NPV). JPY, Japanese yen.

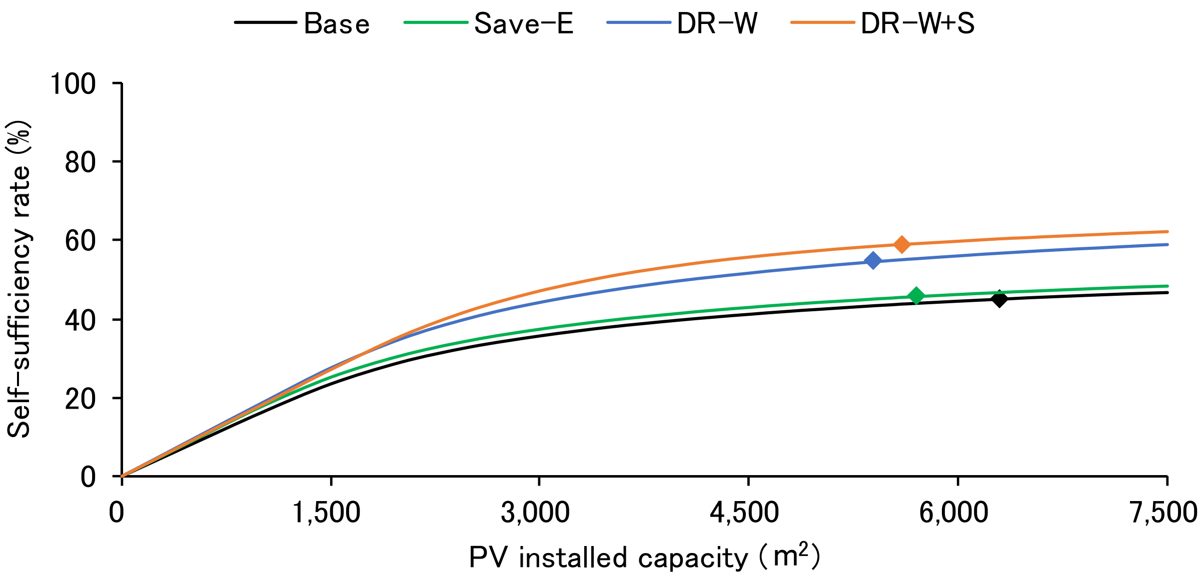
that under the base scenario for the same PV capacity due to reduced daytime electricity consumption for the OD process. Load shifting under the DR-W scenario reduces the PV power surplus during PV generation hours and reduces grid power consumption at night, contributing to higher self-consumption and sufficiency rates, respectively. The DR measure for sludge treatment to reduce the export of PV power surplus in months with a large PV surplus led to a large difference between the DR-W and DR-W+S scenarios with respect to self-consumption rate at the same PV capacity.

It is possible to reach a higher self-sufficiency rate with a smaller PV installation by comparing the base and DR-W scenarios for the same self-sufficiency rate (Fig. 6a); for example, 6000 m^2 is needed to reach 44.3 % under the base scenario versus 3000 m^2 under the DR-W scenario. Load shifting of aeration during high-load operating hours in line with the PV generation curve is more effective at reducing the PV capacity to reach the same self-sufficiency rate than it is at improving the rate for the same PV capacity. Thus, the scale of PV capacity installations should be controlled based on the convergence of the increase in self-sufficiency rate.

4. Conclusions

The aerator has the highest component of electricity consumption in a small-scale WWTP and a high load shift potential. The renewal measures to address the challenges faced by small-scale WWTPs with insufficient capacity utilization can be customized based on DR performances. The excess possessing OD tank can be used as a load adjustment tank, while the automatic aeration system designed for saving energy has the potential for load shifting. The DR measures are effective in matching high-load operation with continuous aeration with the PV daily generation curve; the self-sufficiency rate increased to 54.6 % under the DR-W scenario, which is a 9.8 % increase compared with the base scenario. Annual GHG emissions were reduced by 32.0 % under the DR-W scenario compared with the base scenario by improving the self-sufficiency rate under the condition that electricity demand was met by renewable energy sources. To promote the integration of sludge treatment functions in small-scale WWTPs, the co-treatment of sludge from OWTSs will be considered as a DR measure to consume surplus PV power. The DR measures for the treatment of sludge increased the annual total electricity demand of the WWTP and the self-consumption rate; the estimated NPVs under the DR-W and DR-W+S scenarios were

(a)



(b)

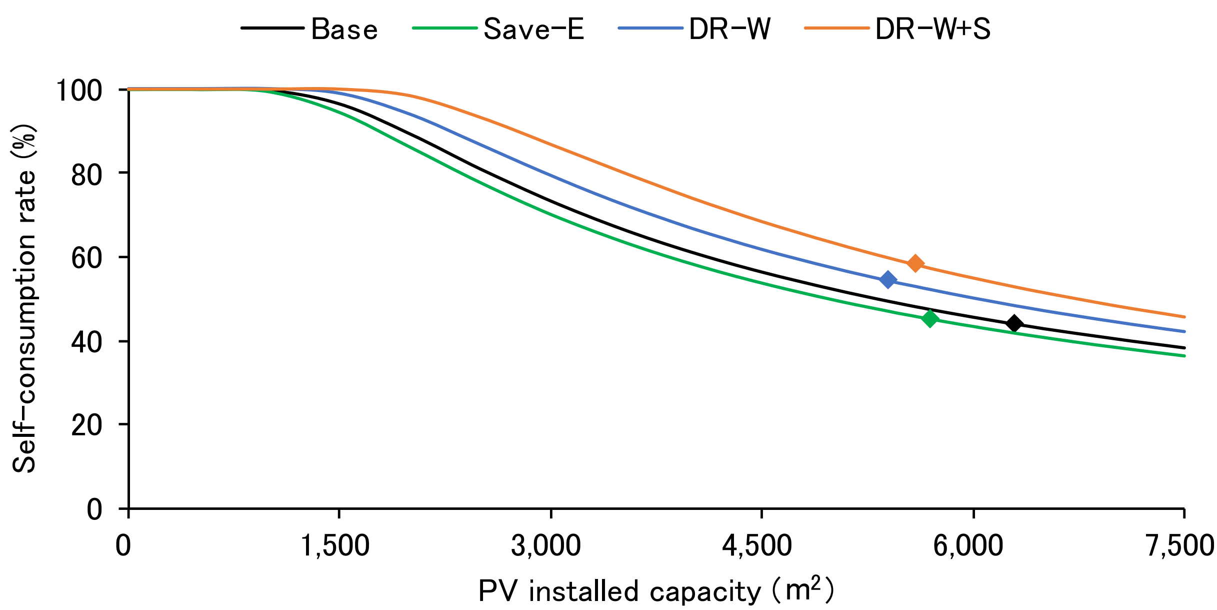


Fig. 6. Estimates for yearly aggregated self-sufficiency (a) and self-consumption (b) rates for changes in installed PV capacity. The plots were constructed under the assumption that the total annual PV power generation and the total annual electricity demand of the wastewater treatment plant were approximately equal: 6300 m^2 under the base case scenario, 5700 m^2 under the Save-E scenario, 5400 m^2 under the DR-W scenario, and 5600 m^2 under the DR-W+S scenario.

approximately equal.

Enhancing case studies to verify the effectiveness of DR measures by the WWTP is a future prospect. Electricity consumption scheduling can be integrated with broader another energy management systems, such as those in decarbonization-oriented residential and commercial districts. Achieving 100 % renewable energy self-sufficiency through the use of storage batteries is a goal that should be pursued for small-scale WWTPs.

CRediT authorship contribution statement

Toyohiko Nakakubo: Writing – original draft, Methodology, Investigation, Conceptualization. **Fumika Okuno:** Visualization, Methodology, Formal analysis. **Seiya Maki:** Validation, Conceptualization. **Yujiro Hirano:** Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the Environment Research and Technology Development Fund [JPMEERF20233004] of the Environmental Restoration and Conservation Agency provided by the Ministry of the Environment of Japan.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145730.

Data availability

Data will be made available on request.

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