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Seasonal Analysis and Capacity Planning of Solar Energy Demand-to-Supply Management: Case Study of a Logistics Distribution Center

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Abstract: In recent years, global warming and environmental problems have become more serious due to greenhouse gas (GHG) emissions. Harvesting solar energy for production and logistic activities in supply chains, including factories and distribution centers, has been promoted as an effective means to reduce GHG emissions. However, it is difficult to balance the supply and demand of solar energy, owing to its intermittent nature, i.e., the output depends on the daylight and season. Moreover, the use of large-capacity solar power generation systems and batteries incurs higher installation costs. In order to maintain low costs, demand-to-supply management of solar energy, based on appropriate seasonal analysis of power generation and consumption and the capacity planning for power generation and the storage battery, is necessary. In this study, the on-demand cumulative control method is applied to actual power consumption data and solar power generation data estimated at a distribution center. Moreover, the monthly, seasonal, and temporal characteristics of power generation and consumption at the distribution center are analyzed. Additionally, the total amount of power purchased is investigated for solar energy demand-to-supply management.

Keywords: solar energy; seasonal power supply and demand analysis; capacity of supply and inventory planning; electricity demand-to-supply management; dynamic inventory control

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1. Introduction

In recent years, the number of adverse environmental events and problems owing to global warming has steadily increased. In order to mitigate these problems, the emission of greenhouse gases (GHGs) must be reduced (Gao et al., 2020) [1]. One solution involves increased usage of renewable energy (Agyekun et al., 2021) [2].

Harvesting solar energy has been promoted as an effective means to reduce GHG emissions (Kasagi, 2021) [3], primarily because harvesting solar energy does not use any fossil fuels that generate GHG emissions. Furthermore, the utilization of solar power generation for production and logistics activities in the supply chain, including factories and distribution centers, can reduce a significant portion of GHG emissions. It has been found that 25.3% of GHG emissions are generated from the production sector of Japan. (Ministry of the Environment and National Institute for Environmental Studies) [4]. Therefore, reducing GHG emissions is necessary for creating a sustainable supply chain. Moreover, using renewable energy, which has less GHG intensity, is necessary in the field of electricity for the supply chain primarily because electricity is used in almost all of the activities for production and logistics. In order to overcome this problem, reduction in GHG emissions is essential in the field of supply chain. However, balancing the supply and demand of solar power is difficult owing to the intermittent characteristics of solar power generation. First, the amount of solar power generation depends on the weather and the availability of sunlight, which changes randomly. One solution to address the variations in power generation by solar energy involves the utilization of batteries. However, the use of large-capacity batteries results in higher installation costs. Additionally, the use of storage batteries results in a loss of power storage once a storage battery is fully charged. In other words, the amount of energy that can be stored is limited. Therefore, capacity planning for power generation and the storage battery is needed when a solar power generation system is installed in an existing facility. Moreover, installation costs for solar power generation systems and storage batteries are expensive. Therefore, economical and effective capacity planning is required to balance solar power generation and power consumption.

Second, the annual power consumption is dependent on the characteristics of the facility and season. For example, power consumption differs among facilities in the supply chain, such as production facilities and distribution centers, even if it is in the same season owing to differences in characteristics, such as scale and internal conditions. Moreover, the total power consumption depends on the season, owing to the usage of air conditioning. To balance between power supply and demand, solar power demand-to-supply management is required (Baker et al., 2013) [5]. In order to implement solar power demand-to-supply management, it is necessary to survey the impact of various factors, such as energy consumption by a facility based on the type and time of usage, scale of solar power generation, and storage battery capacity.

Table 1 presents literature reviews on renewable energy that have investigated demand-to-supply management.

Regarding renewable energy management, Trappey et al. (2013) [6] developed a hierarchical installation cost learning model to model and forecast wind energy development. However, they did not consider the dynamic change in power supply and demand. Pham et al. (2019) [7] proposed a joint production scheduling and microgrid sizing model. Their integrated model was optimized for production scheduling to cover the uncertain demand and sizing and siting of the microgrid systems to adapt to the electric load of multiple facilities. The results of using their model show that combining storage battery systems with solar power generation has a high cost-effectiveness. However, they did not conduct solar energy demand-to-supply management based on forecasted power generation and consumption data. Behzadi et al. (2023) [8] proposed a solution to minimize the footprint of smart building energy systems and enable the increased usage of solar and biomass energy. The result of their model shows that the solution is to enable repayment of the energy purchase amount during cloudy days and nights through the sale of excess renewable energy production. However, they did not consider the change in the power consumption trend. Huy et al. (2023) [9] introduced a home energy management system model. Their model can optimize the energy cost, peak-to-average ratio, and discomfort index using a multi-objective mixed-integer linear programming paradigm. The system is confirmed to be a viable approach for optimally coordinating different home devices. However, they did not conduct the seasonal analysis of renewable energy demand-to-supply management. Gelchu et al. (2023) [10] investigated the contribution of implementing demand-side management to solar PV-based autonomous mini-grids in non-electrified rural areas. Based on their results, the household and productive grids could be reduced by 45.8% and 20.7%, respectively, for a levelized energy cost by implementing demand-side management. However, they used weekly data and did not treat the differences in power consumption for different periods. Al-Habaibeh et al. (2023) [11] investigated the major factors that influence solar energy installation by conducting a questionnaire survey in Jordan. The results of their survey show that a majority of Jordanians believe that both the cost and awareness are crucial when installing solar energy systems. However, they performed a quantitative evaluation of the effectiveness of installing solar energy systems. Biazetto et al. (2023) [12] proposed an optimal control strategy for aiming to regulate the captured solar energy and to manage properly the charge and discharge of thermal energy storage (TES) systems. The TES system maximizes the revenue with a variable energy tariff by a nonlinear programming algorithm. They found potential gains up to 13.5% in terms of annual revenue. However, they did not conduct the seasonal analysis of renewable energy demand-to-supply management.

Shi et al. (2022) [13] applied a hierarchical optimization algorithm to jointly plan the capacity of renewable power and energy storage system (ESS) by the golden section Fibonacci tree optimization algorithm. They improved the computational accuracy and the hierarchical distributed control strategy and found that the hierarchical distributed control strategy was more effective than the single-level control when dealing with multi-objective and high-dimensional systems. However, they considered only renewable energy generation and ESS. They did not consider the management of renewable energy with the demand of power consumption.

Regarding the stochastic model, it is helpful to conduct solar energy demand-to-supply management because the amount of solar power generation and consumption depends on time, day, and season. Therefore, the use of a stochastic model is required to overcome the uncertainties in supply and demand. Mohebi and Roshandel (2023) [14] developed a linear optimization framework for a solar energy system with heat storage to fulfill the agricultural greenhouse heating road. The proposed framework could obtain 89.5% less GHG emissions than the minimum-cost solution. However, they did not conduct demand forecasting based on real power consumption data. Romero-Ramos et al. (2023) [15] evaluated the potential of solar power generation to satisfy the heat demands in an industrial area in southeastern Spain. Their results indicated that 5% of the total area of southeastern Spain is an effective territory to develop an industrial area supplied by solar energy. However, they did not consider the differences in the power consumption characteristics by facility.

With respect to forecasting, Rentizelas et al. (2012) [16] examined the effect that multiple scenarios for the change in emission allowance cost had on the future power generation mix of Greece. They formed a forward-sweeping linear programming model and minimized the annual cost required to generate excess energy. However, they did not conduct solar energy demand-to-supply management monthly or seasonally. Ledmaoui et al. (2023) [17] investigated solar energy production forecasting using six types of machine learning algorithms: support vector regression, artificial neural network (ANN), decision tree, random forest, generalized additive model, and extreme gradient boosting. They showed that using an ANN was the most effective predictive model for energy forecasting. However, they did not consider balancing solar power generation and power consumption.

For energy demand-to-supply management, Zhang et al. (2022) [18] developed an event-triggered distributed hybrid control scheme to achieve security and economic operation for the integrated energy system (IES) by the consensus algorithm and the event-triggered mechanism. They designed the sampling strategy properly to reduce the amount of communication without affecting the achievement and fit well with the multi-time-scale characteristic of the IES. However, they did not perform a quantitative evaluation of the effectiveness of renewable energy systems. Yang et al. (2023) [19] proposed a hybrid policy-based reinforcement learning (HPRL) adaptive energy management to realize the optimal operation for the island group energy system with energy transmission–constrain by reinforcement learning. By treating discrete continuous hybrid actions using HPRL, they could solve the energy management problem of the island group. However, they did not conduct an analysis that considered the seasonal characteristics of renewable energy.

Ijuin et al. (2022) [20] applied an on-demand cumulative control method (Matsui et al., 2005) [21] to actual solar energy production and consumption data in a childcare facility. On-demand cumulative control is a demand-to-supply management method that enables adjusting the base supply in response to changes in the demand structure and on-demand alterations in the input at the next period in inventory management. They estimated the subsequent power purchase amount, frequency, and storage opportunity loss. Consequently, it was found that the childcare facility had the potential to reduce the total amount of power purchased. Kato et al. (2022) [22] applied a job shop control policy to perform solar energy demand-to-supply management in the same childcare facility and demonstrated a reduction in the amount of power purchased after storage installation. However, in both studies, data collection was limited to only one week. Moreover, they only evaluated one type of season and facility in their studies, even though weather conditions are seasonal.

One of the problems with seasonal mismatches between solar power generation and consumption is that solar power cannot be stably supplied, as it depends on different solar radiation for the four seasons in Japan. On the other hand, solar power generation in summer is not stable owing to solar radiation reduction by bad weather. The on-demand cumulative control method enables us to respond by determining an appropriate amount of storage in advanced periods by forecasting the amount of consumption and solar power generation in the next period. Therefore, seasonal mismatches between power generation and consumption could be balanced by the proposed method.

When compared with other methods in previous studies, the on-demand cumulative control method includes not only solar power generation but also the power purchased from the electric power company. Therefore, solar power generation is stored, and the small-scale power consumption demands are covered by power purchased, owing to the preparation for large-scale power consumption demands. In other words, the on-demand cumulative control method enables us to smooth the demand-to-supply management.

In this study, the on-demand cumulative control method is applied to actual power consumption data and estimated solar power generation data at a distribution center that uses solar energy and batteries for seasonal analysis and capacity planning. Subsequently, the total purchased amount is investigated for solar energy demand-to-supply management. Thus, the following research questions (RQs) are raised:

RQ1. How much are differences between the amount of power generation and power consumption monthly or seasonally?
RQ2. How much does the total power purchase amount change when the scale of power generation or storage capacity are increased?
RQ3. How much the solar power generation scale and the storage capacity are required to reduce the total power purchase amount through solar energy demand-to-supply management that makes it economical and effective?
RQ3. What are the advantages of the proposed method compared to the conventional purchasing method for the supply shortage in terms of the total power purchase amount?

Table 1. Literature review on renewable energy treating demand-to-supply management.

	Type of Renewable Energy				Demand-to-Supply			Overcoming Uncertainties				
	Solar	**Wind**	**Biogas**	**Biomass**	**Supply**	**Demand**	**Battery Capacity**	**Stochastic Model**	**Forecasting**	**Real Data**	**Monthly and/or Seasonal Analysis**	**Methods**
Trappey et al. (2013) [6]		√					√		√	√		Hierarchical learning model
Pham et al. (2019) [7]	√	√			√	√	√	√				Stochastic planning model
Rentizelas et al. (2012) [16]	√	√		√	√	√		√	√	√		Forward-sweeping linear programming
Behzadi et al. (2023) [8]	√			√		√				√	√	Transient system simulation tool and programming
Huy et al. (2023) [9]	√				√	√	√	√				Multi-objective mixed-integer linear programming
Al-Habaibeh et al. (2023) [11]	√					√		√		√		Questionnaire survey
Mohebi and Roshandel (2023) [14]	√				√	√		√			√	ε constraint method
Gelchu et al. (2023) [10]	√				√	√	√	√		√	√	Particle swarm optimization
Ledmaoui et al. (2023) [17]	√				√			√	√	√	√	Support Vector Regression, Artificial Neural Network, Decision Tree, Random Forest, Generalized Additive Model Extreme Gradient Boosting
Romero-Ramos et al. (2023) [15]	√		√	√	√	√		√		√		Geographic information system and Analytic hierarchy process
Ijuin et al. (2022) [20]	√				√	√	√	√	√	√		On-demand cumulative-control method
Kato et al. (2022) [22]	√				√	√	√			√		Job shop control policy
Biazetto et al. (2023) [12]	√				√		√			√		Nonlinear programming algorithm
Zhang et al. (2022) [18]					√		√					Containment algorithm, Consensus algorithm, and Event-triggered mechanism
Yang et al. (2022) [19]					√	√	√	√	√	√		Reinforcement learning
Shi et al. (2022) [13]					√		√	√		√	√	The golden section Fibonacci tree optimization algorithm
This study	√				√	√	√	√	√	√	√	On-demand cumulative-control method

2. Methods

In order to conduct the demand-to-supply management and capacity planning, Chapter 2 presents the procedure adopted in this study. Section 2.1 shows the demand-to-supply management procedure. Section 2.2 models demand-to-supply management for solar power generation and power consumption with batteries. Section 2.3 describes the overview of solar power generation and consumption data at a target facility.

2.1. Analysis Procedure

Figure 1 illustrates the analysis procedure of this study and the relationship between the procedure of this study and the research questions. The procedures comprise five steps.

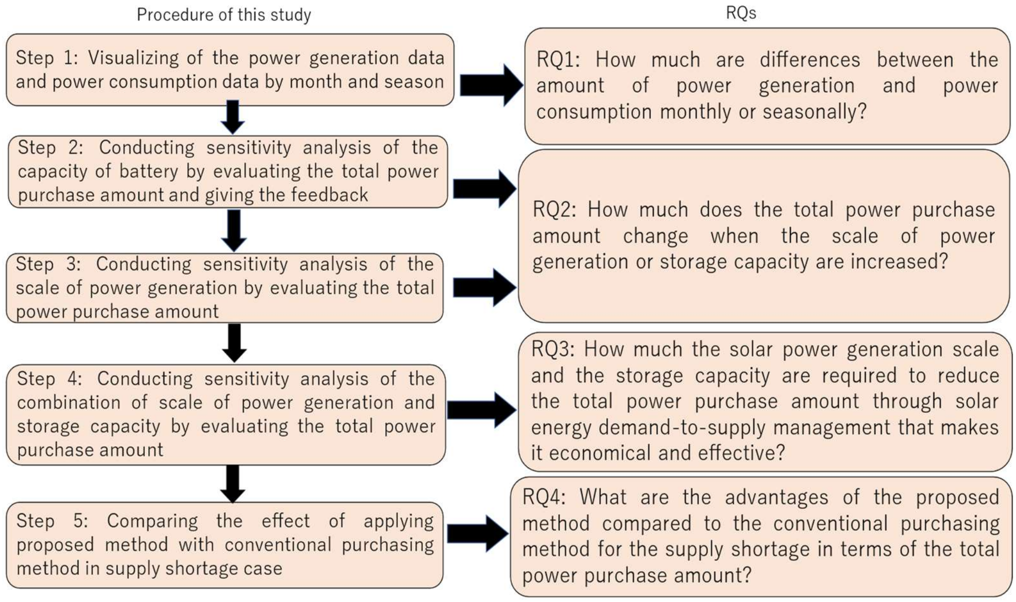

Figure 1. Analysis procedure of this study and research questions (RQs).

The first step involves visualizing the monthly and seasonal power generation and consumption data to investigate how much power is required over different periods.

The second step entails applying the on-demand cumulative control method to the annual solar power generation and consumption data to calculate the hourly power purchase amount. Additionally, a sensitivity analysis of the storage battery capacity was performed by evaluating the total power purchase amount based on the results of the on-demand cumulative control method, and the economic feasibility and effectiveness of the storage capacity were evaluated. Moreover, up to this step, the feedback for this was provided by Ecolomy Co., Ltd. (Tokyo, Japan), a renewable energy consulting company [23].

In the third step, a sensitivity analysis of the scale of solar power generation was conducted by evaluating the total power purchase amount based on the results of the on-demand cumulative control method. Additionally, an evaluation of the economical and effective scale of solar power generation was implemented based on the feedback in the second step.

In the fourth step, a sensitivity analysis of the combination of scale of power generation and storage capacity was performed by evaluating the total amount of purchased power based on the results of the on-demand cumulative control method. Moreover, the economical and effective combination of the scale of power generation and storage capacity was evaluated.

In the final step, the effect of applying the proposed method was compared with the conventional purchasing method for the supply shortage to evaluate the advantage of applying the proposed method.

The methodology used in this article to evaluate the total power purchased is the on-demand cumulative control method [21] and the conventional purchasing method for the supply shortage.

The on-demand cumulative control method calculates the appropriate power supply amount in the next period by forecasting the amount of power generation and consumption in advance. On the other hand, the conventional purchasing method for the supply shortage does not use supply and demand forecasting. Therefore, the conventional method is the method of calculating the electricity amount which could not be covered by the power supply. Additionally, the conventional purchasing method for the supply shortage defines the calculated value as the power purchase amount. Thus, the conventional purchasing method for the supply shortage performs demand-to-supply management using a battery, but it does not use demand forecasting of power consumption.

2.2. Solar Energy Demand-to-Supply Management Model

A model that treats the relationship among supply, inventory, and demand in the case of solar energy is required to conduct solar energy demand-to-supply management. Figure 2 shows the demand-to-supply management model (Ijuin et al., 2022) [20] for solar energy based on the relationship among the supply, demand, and inventory. Private power generation in period t, S_t, and power purchase amount P_t represent the supply of electricity. The demand indicates the amount of power consumption in period t, O_t. The inventory amount is the charge amount in period t, L_t, and storage capacity L_{max}, which indicates the storage battery capacity in the solar energy system (Matsui et al., 2005) [21].

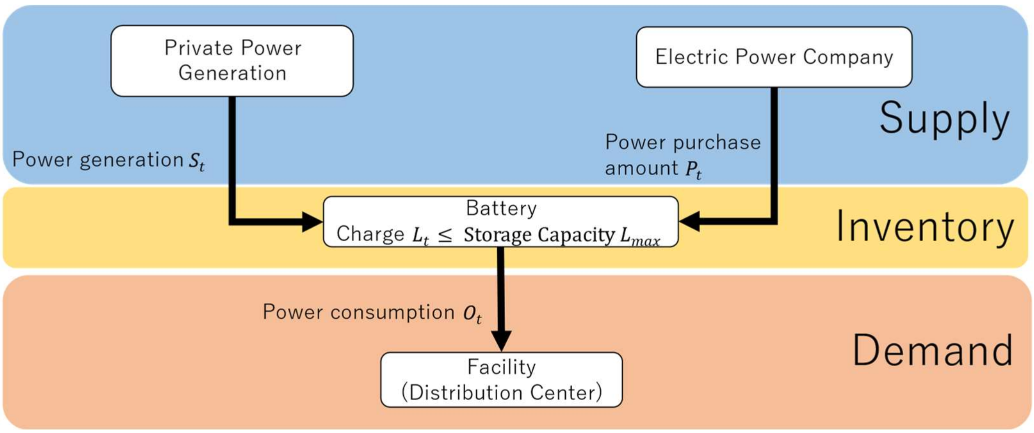

Figure 2. Solar energy demand-to-supply management model.

2.3. Power Consumption and Solar Power Generation Data at the Target Facility

In order to analyze the annual solar power generation and power consumption data and plan the capacity of the power generation scale and battery, the annual estimated power generation and real consumption data are needed for demand-to-supply management.

Table 2 presents an overview of power generation and consumption data. In this study, the annual power consumption data at a distribution center in Yokohama, Japan that treats food products were used, and the consumption data were provided by Ecolomy Co., Ltd. [23]. The hourly data are recorded annually.

However, the actual solar power generation data are unknown before the new solar power generation system was installed. Thus, synthetic solar power generation data are estimated. It is assumed that the distribution center is equipped with 20 kW photovoltaic panels. The power generation data were estimated based on the volume of daily solar radiation, obtained from the New Energy and Industrial Technology Development Organization (NEDO, 2021) [24].

Table 2. Overview of synthetic power generation and actual consumption data.

Data Attributes	This Study
Target facility	Distribution center in Yokohama, Japan
Measurement period	From March 2020 to February 2021
Measurement interval	One hour
Power generation data	Estimated based on actual solar radiation data provided by NEDO [24] by applying proposed method
Power consumption data	Actual data provided by Ecolomy Co., Ltd. [23].
Panel power generation capacity	20 kW
Usage of power consumption	Air conditioning, Lightning, Refrigeration and Freezing

3. Data Processing of Solar Energy Demand-to-Supply Management

In order to perform demand-to-supply management for solar energy, the data need to be processed and the total power purchase amount needs to be estimated. Therefore, this chapter describes the on-demand cumulative control method, which is a data processing method. Section 3.1 illustrates the overview of the on-demand cumulative control method. Moreover, the parameters used in the proposed method are described as shown in Table 3. Section 3.2 outlines the procedure of estimating the amount of total power purchased using the on-demand cumulative control method. Section 3.3 indicates the elaboration on the data sources and parameters in our study as shown in Tables 4 and 5.

3.1. Overview of the On-Demand Cumulative Control Method Application

The on-demand cumulative control method (Ijuin et al., 2022) [20] is a demand-to-supply method based on the inventory control method proposed by Matsui et al. (2005) [21]. It enables the adjustment of base supply in response to changes in the demand structure and the on-demand alterations in subsequent input inventory management. In this study, the on-demand cumulative control is applied to analyze the estimated power generation and real power consumption data.

Additionally, solar energy demand-to-supply management is implemented and analyzed to reduce the total amount of power purchased. Notations used in this paper are listed in Table 3.

Table 3. Notations used in this study.

Variables	This Study
O_t	Power consumption in period t [kWh]
N_t	Moving base storage amount in period t [kWh]
L_t	Remaining storage amount in period t [kWh]
$\overline{\beta_t}$	Input amount determination parameter in period t
S_t	Power generation in period t [kWh]
λ_t	Demand rate at period t
P_t	Power purchase amount in period t [kWh]
$I't$	The amount of power supply in the next period in period t [kWh]
X_t	Forecasted power consumption [kWh]
Y_t	Forecasted power generation [kWh]
L_{init}	Initial storage amount [kWh]
L_{max}	Storage capacity [kWh]
HAm_t	Total solar irradiation in period t per array plane [kWh/m^2]

Table 3. *Cont.*

Variables	This Study
Coefficient	
α	Smoothing coefficient
K	The coefficient total design factor
PAS	Panel power generation capacity [kW]
Gs	Standard irradiance per array plane [kW/m^2]
Evaluation Value	
TP	Total power purchase amount [kWh]

3.2. Procedure of Applying the On-Demand Cumulative Control Method

The procedure and formulation for applying the on-demand cumulative control method [20] are depicted in Figure 3. The procedure for the proposed method in this study contains the solar power generation estimation step which shows step (a) in addition to the procedures (b) to (g) for applying the on-demand cumulative control method in Ijuin et al. (2022) [20]. In step (a), the coefficient total design factor K, the panel power generation capacity PAS, the total solar irradiance in the period t per array plane HAm_t, and standard irradiance per array plane Gs are used to calculate the estimated amount of solar power generation S_t, as shown in Equation (1) (Kurokawa et al., 2016) [25].

$$S_t = K \cdot PAS \cdot \frac{HAm_t}{Gs} \tag{1}$$

From step (b) onward, the procedure for applying the on-demand cumulative control method of Ijuin et al. (2022) is followed [20].

In step (b), the following parameters are set to their initial values: coefficient α $(0 \leq \alpha \leq 1)$ used in the exponential smoothing method (Asada et al., 2004) [26], initial input amount determination parameter $\overline{\beta_0}$ $\left(0 \leq \overline{\beta_0} \leq 1\right)$, initial storage amount L_{init}, and cumulative probability distribution with charge amount L_t, $F(L_t)$.

In step (c), the forecasted power consumption and generation X_{t+1} and Y_{t+1}, respectively, are calculated using the exponential smoothing method (Asada et al., 2004) [26], which uses the power consumption over period t, O_t, and power generation over period t, S_t, as expressed in Equations (2) and (3).

$$X_{t+1} = \alpha O_t + (1 - \alpha) X_t \tag{2}$$

$$Y_{t+1} = \alpha S_t + (1 - \alpha) Y_t \tag{3}$$

In step (d), the moving base storage amount N_t is calculated using Equation (4).

$$N_t = F^{-1}\left(\overline{\beta_t}\right) \tag{4}$$

In step (e), the input amount determination parameter over period t, $\overline{\beta_t}$ is updated using the demand rate over period t, λ_t, as shown in Equation (5) (Matsui et al., 2009) [27].

$$\overline{\beta}_{t+1} = \frac{\lambda_t}{\lambda_{t+1}} \overline{\beta_t} \tag{5}$$

In step (f), the amount of power supply in the next period in period t, I'_{t+1} is calculated using Equation (6), which is the final output of the on-demand cumulative control method in inventory management (Matsui et al., 2005) [21].

$$I'_{t+1} = X_{t+1} + N_t - L_t \tag{6}$$

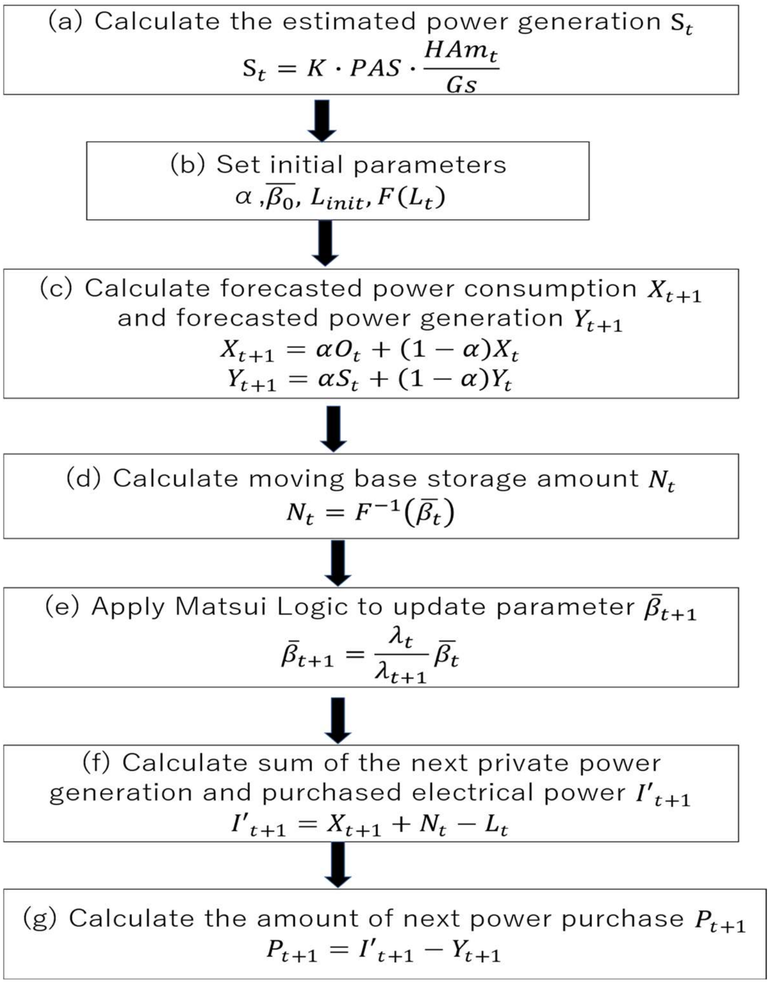

Figure 3. Proposed procedure for applying the on-demand cumulative control method based on Ijuin et al. (2022) [20].

In step (g), the subsequent power purchase amount P_{t+1} is calculated using Equation (7).

$$P_{t+1} = I'_{t+1} - Y_{t+1} \tag{7}$$

3.3. Explanation about the Data Sources and Parameters

In this study, several parameters are used for applying the proposed method. In order to elaborate on them, Section 3.3 illustrates the explanation and usage of the parameters. Table 4 shows the explanation and usage of parameters whose values are defined by the real data or initial setting in the proposed method. Table 5 indicates the explanation and usage of parameters whose values are calculated by the proposed method.

Table 4. List of parameters from real data or initial setting.

Parameters	Data Source or Explanation about Parameters	Value
Power consumption in period t O_t [kWh]	The power consumption in period t, O_t shows actual amount of power consumption in period t. It is shown as real data at the target facility provided by Ecolomy Co., Ltd. [23]. It is recorded annually and hourly.	Varies by t
Initial storage amount L_{init} [kWh]	The initial storage amount L_{init} indicates the storage amount in period $t = 0$. The value of L_{init} is unified as 0 [kWh].	0 [kWh]
Storage capacity L_{max} [kWh]	The storage capacity L_{max} indicates the maximum amount of electricity which can be stored in storage battery.	Varies by scenario
Total solar irradiation in period t per array plane HAm_t [kWh/m^2]	The total solar irradiation in period t per array plane HAm_t shows the actual total solar irradiation in period t per array plane. The source of HAm_t is numerical data at the target facility area, which are provided by the New Energy and Industrial Technology Development Organization (NEDO, 2021) [24]. It is recorded annually and hourly.	Varies by t
Smoothing coefficient α	The smoothing coefficient α shows the degree of consideration of actual value when the power generation or consumption forecasting is conducted. α is used in the proposed method to calculate the forecasted power consumption X_t and power generation Y_t. The value of α is unified as 0.5.	0.5
The coefficient total design factor K	The coefficient total design factor K indicates the correction of solar power output loss. The cause of occurring output loss has several reasons, such as the dirty part of solar panel and decreasing solar radiation. According to the NEDO [24], K is defined as 0.73.	0.73
Panel power generation capacity PAS [kW]	The panel power generation capacity PAS shows the performance of power generation of the panel. This is used in calculation of the power generation amount. In this study, real data of PAS is at the target facility area, which was provided by Ecolomy Co., Ltd. [23].	20 [kW]
Standard irradiance per array plane Gs [kW/m^2]	The standard irradiance per array plane Gs shows the momentary solar radiation intensity. According to the NEDO [24], K is defined as 1 [kW/m^2].	1 [kW/m^2]

Table 5. List of parameters from calculation.

Parameters	Explanation and Calculation Method	Equation of Calculation	
Power generation in period t S_t [kWh]	The power generation in period t, S_t indicates estimated power generation data in period t. S_t is calculated by the coefficient total design factor K, the panel power generation capacity PAS, the total solar irradiance in period t per array plane HAm_t and standard irradiance per array plane Gs as shown in Equation (8)	$S_t = K \cdot PAS \cdot \frac{HAm_t}{Gs}$	(8)
Forecasted power consumption in period t X_t [kWh]	The forecasted power consumption in period t, X_t shows the power consumption data estimated with using power demand forecasting. X_{t+1} is calculated by the smoothing coefficient α power consumption in period t, O_t as shown in Equation (9)	$X_{t+1} = \alpha O_t + (1-\alpha) X_t$	(9)
Forecasted solar power generation in period t Y_t [kWh]	The forecasted solar power generation in period t, Y_t shows the solar power generation data estimated by using solar power generation forecasting. In the proposed method, Y_{t+1} is calculated by the smoothing coefficient α and the power consumption in period t, S_t as shown in Equation (10)	$Y_{t+1} = \alpha S_t + (1-\alpha) Y_t$	(10)
Remaining storage amount in period t L_t [kWh]	The remaining storage amount in period t, L_t shows the amount of electricity in the storage battery at the end of period t. L_t is calculated by the power consumption in period t, O_t, the estimated amount of power generation in period t, S_t, the power purchase amount in period t, P_t, and the storage capacity, L_{max} as shown in Equation (11). When the sum of power generation in period t, S_t, the power purchase amount in period t, P_t, and L_{t-1} is higher than the actual power consumption in period O_t, L_t is estimated as the smaller value between the difference among them and L_{max}. Otherwise, the value of L_t is recorded 0.	$L_t = \begin{cases} \min(L_{max},\ L_{t-1} + S_t + P_t - O_t) & (L_{t-1} + S_t + P_t \geq O_t) \\ 0 & (L_{t-1} + S_t + P_t < O_t) \end{cases}$	(11)
Demand rate at period t λ_t	The demand rate at period t, λ_t is regarded as the actual power consumption data in period t, O_t. On the other hand, λ_{t+1} is regarded as forecasted power consumption data in period $t+1$, X_{t+1} demand. The reason λ_{t+1} is defined as X_{t+1}, O_{t+1} cannot be found in period t. They are calculated as Equations (12) and (13).	$\lambda_t = O_t$	(12)
		$\lambda_{t+1} = X_{t+1}$	(13)

Table 5. *Cont.*

Parameters	Explanation and Calculation Method	Equation of Calculation
Input amount determination parameter in period t $\overline{\beta_t}$	The input amount determination parameter in period t, $\overline{\beta_t}$ indicates the parameter which updated by the ratio of power consumption in the current period and the next period. $\overline{\beta_t}$ is used to estimate the moving base storage amount. $\overline{\beta_t}$ is calculated as shown in Equation (14) and $\overline{\beta}_0$ is defined 0.5 as initial value in this study.	$\overline{\beta_t} = \begin{cases} \frac{\lambda_{t-1}}{\lambda_t}\overline{\beta}_{t-1} & (t \geq 1) \\ 0.5 & (t = 0) \end{cases}$ (14)
Moving base storage amount in period t N_t [kWh]	The moving base storage amount in period t, N_t means the storage amount which should be charged for effective demand-to-supply management in period t. On the other hand, it shows the appropriate amount of electricity in the storage battery to conduct effective demand-to-supply management. N_t is calculated by the input amount determination parameter over period t, $\overline{\beta_t}$ and cumulative probability distribution of the remaining storage amount L_t, $F(L_t)$ as shown in Equation (15).	$N_t = F^{-1}(\overline{\beta_t})$ (15)
The amount of power supply in the next period in period t I'_t [kWh]	The amount of power supply in the next period in period t, I'_t indicates sum of the next private power generation and purchased electrical power in period t. I'_{t+1} is calculated by the forecasted power consumption in period t, X_t, the moving base storage amount in period t, N_t and the remaining storage amount in period t, L_t as shown in Equation (16)	$I'_{t+1} = X_{t+1} + N_t - L_t$ (16)
Power purchase amount in period t P_t [kWh]	The power purchase amount in period t, P_t indicates the amount of power supply that cannot be covered by the private power generation in period t. P_t is shown the difference between the amount of power supply in the next period in period t, I'_t and the forecasted power generation in period t, Y_t. It is shown in Equation (17).	$P_t = I'_t - Y_t$ (17)
Total power purchase amount TP [kWh]	The total power purchase amount TP indicates the total power purchase amount during the measurement period. TP is calculated in Equation (18).	$TP = \Sigma P_t$ (18)

4. Seasonal Analysis of Power Generation and Consumption

4.1. Results of Monthly Comparison for Power Generation and Consumption (RQ1)

Due to the four seasons in Japan, the amount of daily solar radiation is different for each month or season. Moreover, solar radiation is correlated with the amount of solar power generation. Therefore, the characteristics of solar power generation and consumption differ for each month or season. Figure 4 shows the monthly average amount of solar power generation and daily power consumption to analyze the characteristics of monthly solar power generation and power consumption at the distribution center. In terms of the monthly solar power generation and consumption of the target distribution center, the average daily solar power generation and consumption were 58.1 kWh and 362.9 kWh, respectively, for the entire year.

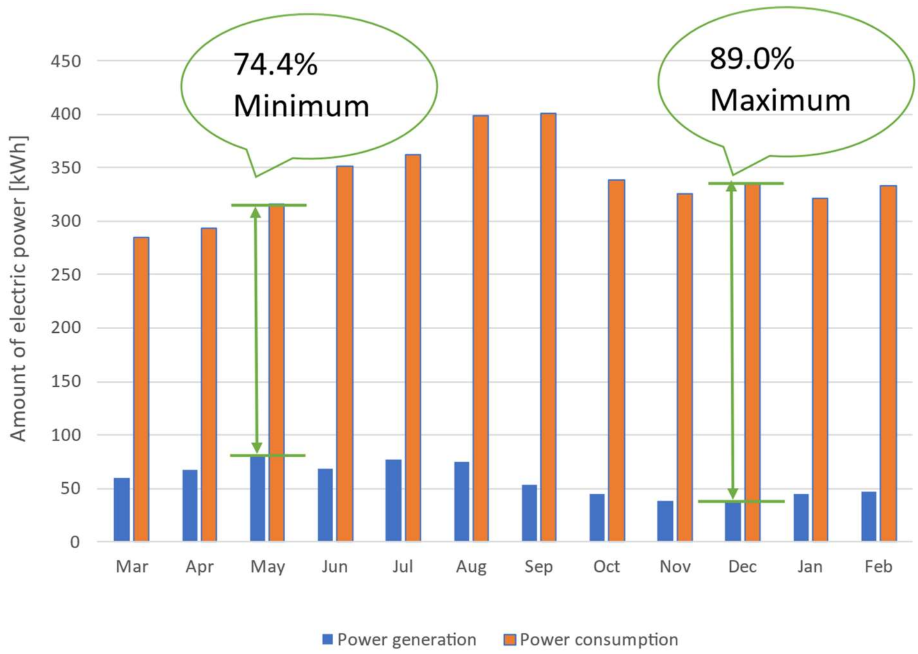

Figure 4. Monthly solar power generation and consumption.

Considering the highest proportion of power generation, it was recorded as 80.8 kWh in May. Conversely, September recorded the maximum power consumption. Moreover, the total power generation was 83.5% less relative to the power consumption at the target facility, and the maximum ratio of the solar power generation was 89.0% lower than the power consumption in December, and the minimum was 74.4% in May. Therefore, power consumption was larger than solar power generation in each month.

4.2. Results of the Seasonal Comparison for Solar Power Generation and Consumption (RQ1)

Figure 5 shows the seasonal average amount of daily solar power generation and daily power consumption for analyzing the characteristics of them at the distribution center. As per the answer to RQ1, the amount of power consumption was approximately four times larger than solar power generation in spring and summer. However, in the autumn and winter, power consumption was approximately seven times larger than solar power generation. Regarding the average daily solar power generation and consumption of the target facility seasonally, in the winter, the season with the lowest solar power generation, solar power generation was 38% lower than that in the summer, the season with the highest solar power generation.

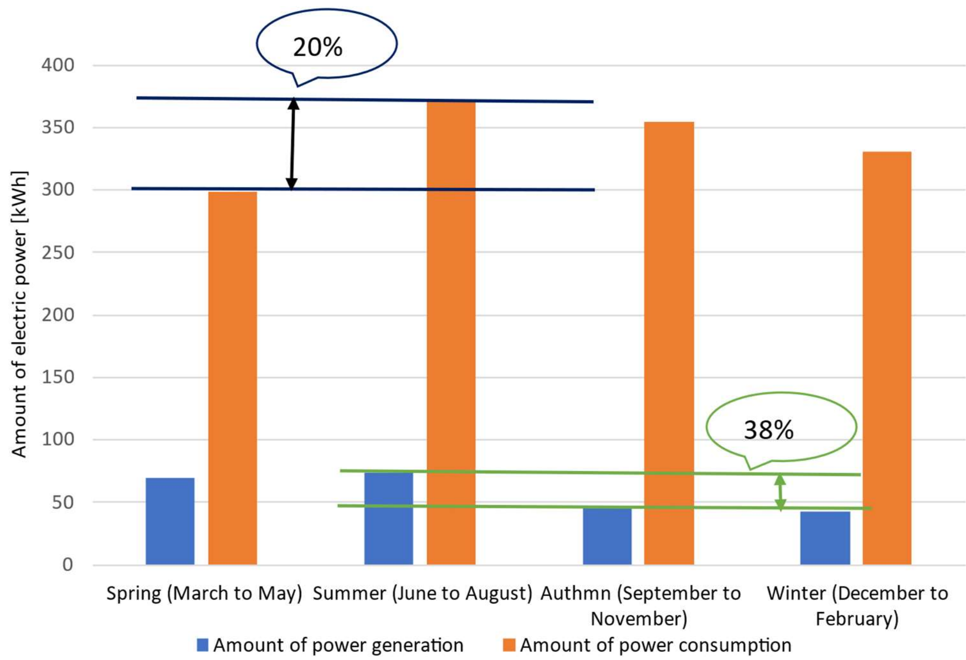

Figure 5. Solar power generation and consumption in each season.

Additionally, the amount of power consumption in the summer, the season with the highest power consumption, was 20% higher than that in spring, the season with the lowest power consumption.

Moreover, solar power generation and consumption are highest during the summer owing to the increase in sunlight hours and the usage of air conditioning owing to the rise in temperature and humidity.

4.3. Results of Daily Power Generation and Consumption at the Target Facility

Sections 4.1 and 4.2 show the comparison of power generation and power consumption data monthly and seasonally. However, when comparing daily solar power generation and consumption, data are also needed to investigate the characteristics of private solar power generation and power consumption at the target facility. Figure 6 shows cumulative solar power generation and consumption data for 14 January 2021, one of the days in which the weather was sunny and usual activities were carried out in the distribution center, with a daily cumulative solar power generation and consumption rate of 100%. Power shortages are observed to occur at night, despite the total solar power generation exceeding the total power consumption.

4.4. Sensitivity Analysis of Total Purchased Power with the Storage Capacity of the Storage Battery (RQ2)

This section discusses the result of the sensitivity analysis of the total power purchase amount TP with the capacity of the storage battery to examine the impact of increasing the storage capacity L_{max}.

The total power purchase amount TP is compared for various storage capacities to investigate the impact of installing batteries on the power purchasing amount. Figure 7 shows the total power purchase amount TP against various storage battery capacities to investigate the effect of increasing the storage capacity L_{max}. When a storage battery with 5 kWh capacity is installed, the total power purchase amount TP decreases by 10.1%. However, Figure 7 also shows that no significant change is observed when the storage capacity L_{max} is increased to more than 5 kWh. This is because the decreased ratio of the total power purchase amount TP is less than 1% when the storage capacity L_{max} is increased to more than 5 kWh. As a solution for RQ2, a large effect of decreasing the total power purchase amount TP is observed when the storage battery has a storage capacity

L_{max} of 5 kWh. Meanwhile, the total power purchase amount TP does not significantly change when the storage capacity L_{max} is increased to more than 5 kWh.

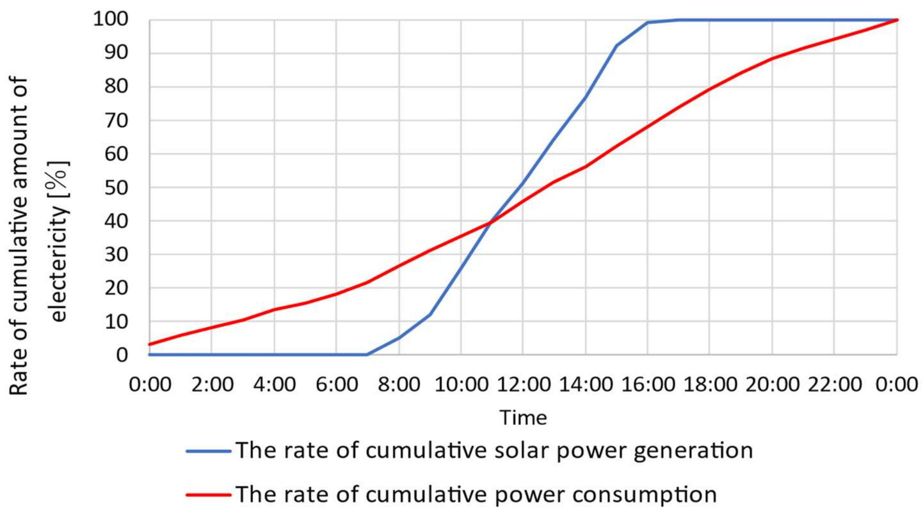

Figure 6. Cumulative power generation and consumption on 14 January 2021.

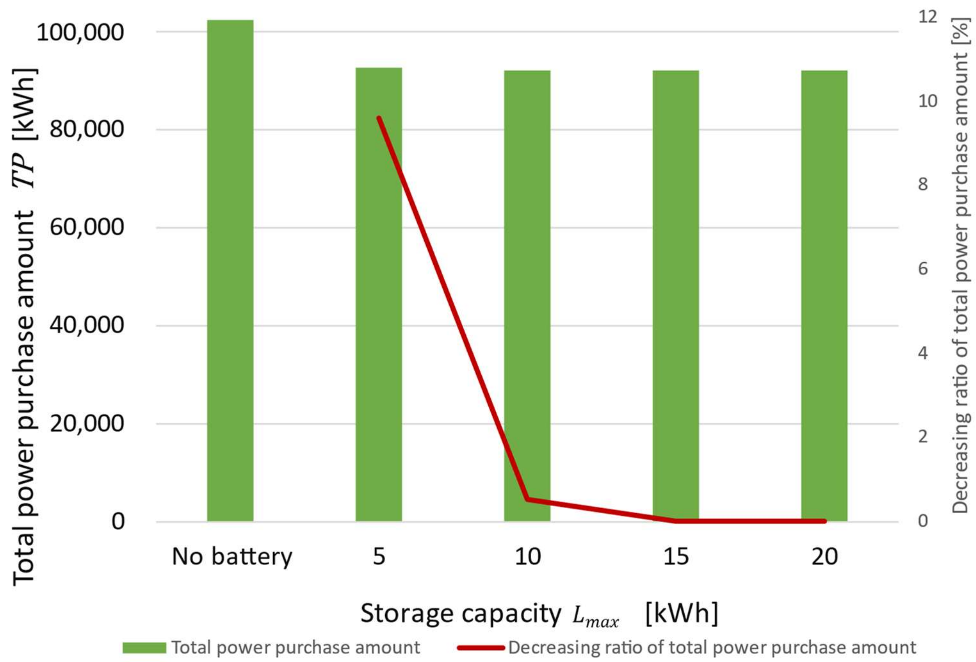

Figure 7. Total and decreasing ratio of power purchase amount TP when a storage battery with different storage capacities is installed.

5. Capacity Planning for Solar Power Generation and Storage Battery

5.1. Sensitivity Analysis of Total Purchased Power with the Scale of Solar Power Generation (RQ2)

In Appendix A.2, the feedback from the renewable energy consulting company (Ecolomy Co., Ltd.) [23] mentioned that the proposed management method has a high potential for decreasing the total power purchase amount TP by expanding the scale of private solar power generation. Thus, Section 5.1 confirms the impact of increasing the scale of solar power generation by applying the on-demand cumulative control method.

The total power purchase amount TP is compared for various scales of solar power generation S_t to investigate the impact of changing the scale of solar power generation S_t on the total power purchase amount TP. Figure 8 shows the total power purchase amount

TP against various scales of power generation S_t to investigate the effect of increasing the scale of solar power generation S_t. When two times the amount of electricity is generated, the total power purchase amount TP decreases by 14.5%. However, this figure also shows that the higher the magnification of electricity generated, the lesser the effect on decreasing the ratio of the total power purchase amount TP. It provides a solution to RQ2; it has a large effect of decreasing the total power purchase amount TP when the scale of solar power generation S_t increases by twice. However, the effect of decreasing the ratio of total power purchase amount TP is small, even if the magnification of solar power generation S_t is increased.

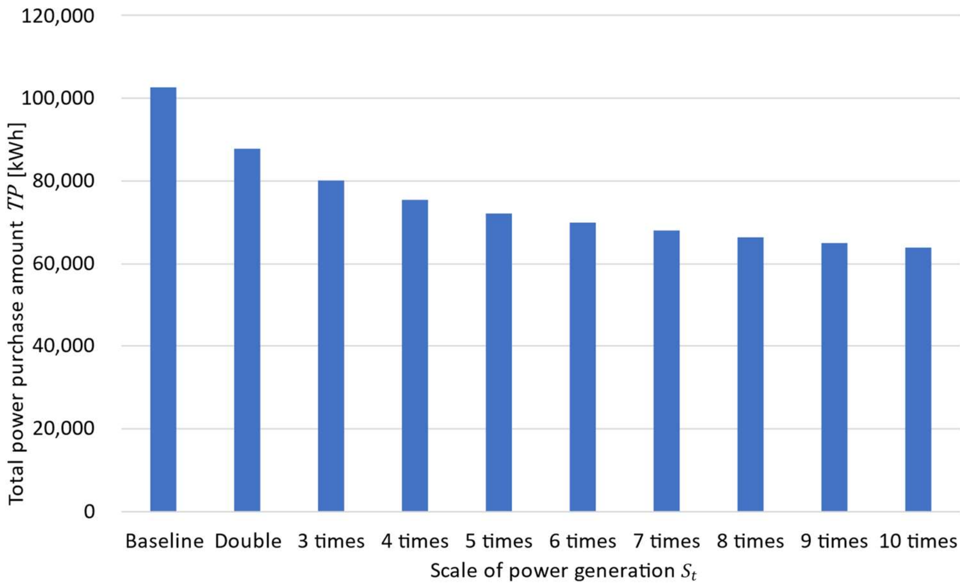

Figure 8. Total power purchase amount TP when the scale of power generation S_t is changed.

5.2. Sensitivity Analysis of the Total Power Purchase Amount with Respect to the Scale of Power Generation and Storage Capacity (RQ3)

In Sections 4.4 and 5.1, the impact on the total power purchase amount TP is investigated by increasing the scale of solar power generation S_t and storage capacity L_{max}. However, the cost of installing solar power generation facilities and storage batteries should be considered in an actual scene. Therefore, to estimate the economic scale of solar power generation S_t and storage capacity L_{max} when the total power purchase amount TP is decreased effectively, the total power purchase amount TP is compared for various scales of solar power generation S_t and storage capacities.

Figure 9 shows the total power purchase amount TP for different scales of solar power generation and storage capacities. The decreasing ratio of the total power purchase amount TP is less than 5% when more than four times the electricity is from privately generated solar power and a 5 kWh storage battery capacity is installed. Accordingly, RQ3 can be addressed as follows: installing four times the amount of power generation S_t and a 5 kWh storage battery could economically and effectively affect reducing the total power purchase amount TP.

5.3. Comparison of Proposed Demand-to-Supply Management Method and Conventional Purchasing Method for the Supply Shortage (RQ4)

The effect of applying the proposed method is shown in Sections 4.4 and 5.1 However, the proposed method should have an advantage compared with the conventional purchasing method for the supply shortage shown in Appendix A1 as Equation (A1). The conventional purchasing method for the supply shortage indicates an electricity purchase method for the rest of the amount of power consumption. Specifically, the power purchase amount P_t is determined as the difference that could not be covered by private power generation S_t and the power in the battery for period t. Therefore, a comparison of the proposed demand-to-supply management method and conventional purchasing method for the supply shortage was conducted to compare the effect of decreasing the total power purchase amount TP with the conventional purchasing method for the supply shortage.

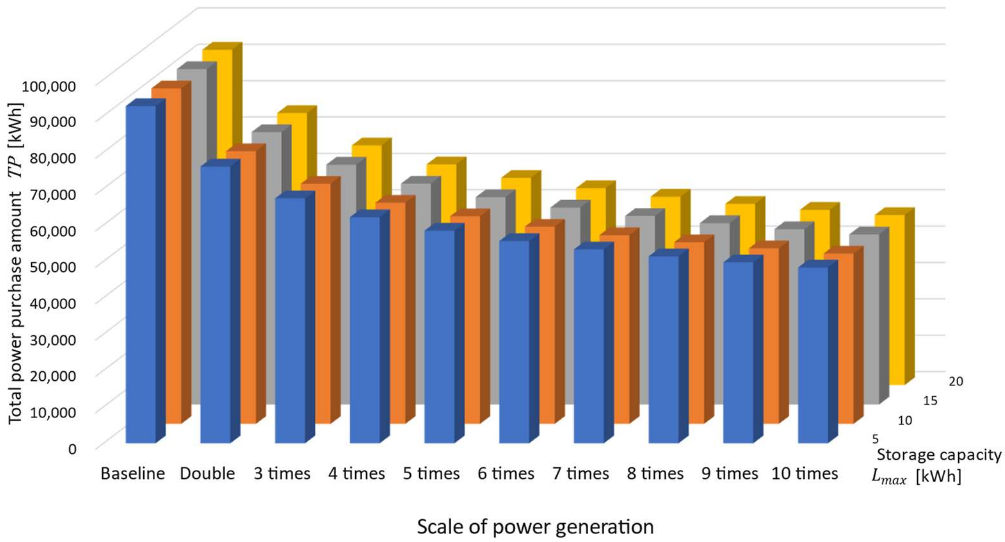

Figure 9. Total power purchase amount TP with sensitivity analysis for different scales of solar power generation S_t and storage capacity L_{max}.

Figure 10 shows the total power purchase amount TP estimated for the case with no battery, the conventional purchasing method for the supply shortage, and the proposed method. The proposed method considers a storage battery installed with a scale of solar power generation S_t that is four times larger and a 5 kWh of storage capacity L_{max}. Evidently, the total power purchase amount TP was 17.6% lower than the case of not installing a battery. The result shows that the proposed method is more effective in reducing the total power purchase amount TP than the method that does not install a battery. Moreover, 7.6% of the total power purchase amount TP was reduced when the proposed method was applied in comparison to applying the conventional purchasing method for the supply shortage.

The appropriate amount of electricity supplied by private power generation S_t, power purchased P_t, and storage in batteries can be calculated in advance when the proposed method is applied, and the larger amount of power consumption O_t is expected in the next period. According to these procedures, the power purchase amount P_t can be reduced when a larger amount of power is consumed.

On the other hand, the conventional purchasing method for the supply shortage did not contain forecasting the power supply and demand. Thus, the appropriate amount of electricity cannot be stored in advance and a large amount of electricity is purchased when a large amount of power consumption occurs. Actually, when the proposed method was applied, there were periods where more than 10 kWh of power purchase amount P_t were reduced per hour in comparison to the conventional purchasing method for the supply shortage. The trouble of decreased power purchase amount P_t occurred between 16:00 and 20:00 when the amount of solar power generation decreased significantly from sun sets.

Therefore, the proposed method can obtain a lower total power purchase amount than the conventional purchasing method for the supply shortage. Thus, RQ4 can be addressed as follows: applying the proposed method could better reduce the total power purchase amount TP than the conventional purchasing method for the supply shortage.

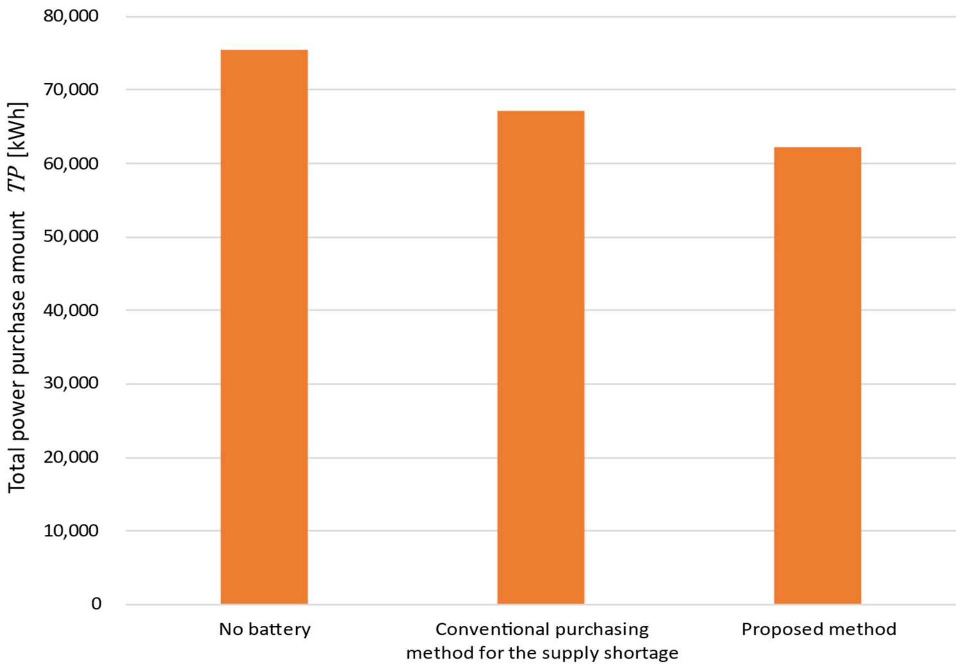

Figure 10. Comparison of conventional and proposed method.

6. Discussion

This chapter discusses the answers from the results in Chapter 4 and Chapter 5 along with RQs in Chapter 1. In a previous study (Ijuin et al., 2022) [20], the data only included one week in late August. Therefore, the impact on the demand-to-supply management seasonality was not considered. It is not desirable to perform demand-to-supply management without considering the change of seasons. This is because the supply and demand situation of electricity depends on the season, thus, appropriate management may change accordingly because the amount of sunlight varies with the seasons. The new findings are included from the seasonal and annual power consumption data at the distribution center as follows.

RQ1. How much are differences between the amount of power generation and power consumption monthly or seasonally?

As per the answer to RQ1, based on the results in Sections 4.1 and 4.2, the amount of power consumption was approximately four times larger than solar power generated in spring and summer. However, in autumn and winter, the power consumption was approximately seven times larger than the power generation at the facility. Additionally, the total amount of power consumption was 5.82 times higher than the total amount of solar power generation at the distribution center. Therefore, it is impossible to cover the amount of required solar power generation for the distribution center only by their private solar power generation.

Therefore, the amount of power consumption needs to be reduced, mainly in the period in which little solar power is generated owing to the lack of solar radiation in the facility.

RQ2. How much does the total power purchase amount change when the scale of power generation or storage capacity are increased?

The answer to RQ2 is based on the results in Sections 4.4 and 5.1. The total power purchase amount decreased by 14.5% when the scale of solar power generation increased by twice. However, there was a small effect on the decreasing ratio of total power purchase amount even when there was a higher magnification of solar power generation. In fact, when the magnification of solar power generation increased from four to five times, the total power purchase amount decreased to less than 5%. Moreover, the total power purchase amount decreased by 10.1% when the installed storage battery had a storage capacity of 5 kWh. On the other hand, the total power purchase amount had no significant change when the storage capacity was increased to more than 5 kWh. Therefore, the scale of the solar power generation system and storage capacity could be determined and designed based on the gap between power generation and consumption. Moreover, a key contribution of this study is that the proposed method enables us to plan capacities for the most economical value of the scale of solar power generation and storage capacity when a solar power generation system and storage battery are installed.

RQ3. How much the solar power generation scale and the storage capacity are required to reduce the total power purchase amount through solar energy demand-to-supply management that makes it economical and effective?

The answer to RQ3 is based on the results in Section 5.2, which are based on the results of Sections 4.4 and 5.1, the decreasing ratio of the total power purchase amount was 14% when the scale of solar power generation was expanded by twice. Moreover, 10.1% of the total power purchase amount was reduced when the storage capacity of the installed storage battery was 5 kWh. However, the decreasing ratio of the total power purchase amount was under 5% when the generated electricity was five times higher. On the other hand, no significant change occurred even if the storage capacity was increased to more than 5 kWh. More specifically, in bad weather or when there is no sunlight at night, little electricity is generated by private solar power generation, and a power consumption of at least 5 kWh occurs per hour in the distribution center, even during the night. Thus, the power purchased was mainly acquired at night or in bad weather even if private power generation and storage capacity are increased. Moreover, a larger amount of solar power generation, almost four times, and installing a storage battery with a storage capacity of 5 kWh could be economical and effective to reduce the total power purchase amount in this facility. Therefore, another key contribution of this study is that the proposed method enables us to plan capacities for the most economical value of the scale of solar power generation and storage capacity when a solar power generation system and storage battery are installed.

RQ4. What are the advantages of the proposed method compared to the conventional purchasing method for the supply shortage in terms of the total power purchase amount?

The answer to RQ4 is based on the results in Section 5.3. Applying the proposed method could reduce the total power purchase amount by 7.6% because adapting the tendency of power consumption for on-demand could be more effective via dynamic demand forecasting using the proposed method than using the conventional purchasing method for the supply shortage. Therefore, applying the proposed method can effectively manage the amount of the next input of electricity and adapt to the change in demand tendency in short periods in terms of the total amount of power purchased. Accordingly, the advantages of the proposed method are highlighted when a solar power generation system is installed, and solar energy demand-to-supply management is performed using the proposed method.

This study has two core innovations. One of the core innovations is that the seasonal analysis is applied to the demand data of power consumption. The seasonal analysis revealed that the maximum gap between the amount of solar power generation and the amount of power consumption was 14.6% depending on the month in the target facility, even if the facility had the same capacity of solar panels. In other words, there are months when the power should be purchased because the amount of solar power generation is insufficient, such as in the winter from September to November. On the other hand, there are months which are necessary to dispose of the power because the amount of solar power generation is excessive, such as in the spring from March to May. Therefore, demand-to-supply management could appropriately control the power imbalances to mitigate the seasonal gap in solar power generation.

Another core innovation is that the proposed method for solar energy demand-to-supply management demonstrates the potential to reduce the annual total purchase amount. For example, the total power purchase amount was reduced by 7.6% when the proposed method was applied instead of the conventional purchasing method for the supply shortage case.

7. Conclusions and Future Studies

This study applied the demand-to-supply management for solar energy at the distribution center by using the on-demand cumulative control method. The results show that the method enables us to determine the storage capacity based on the annual power consumption and estimated solar power generation. Thereby, the total power purchase amount was effectively reduced in the distribution center as well as a childcare facility. Therefore, one of the contributions of this paper is that the proposed method enables us to plan capacities for the economical value for the scale of solar power generation and storage capacity when solar power generation systems are installed with storage batteries.

Future studies will consider the following. First, the cost of installing panels and batteries should be considered when conducting solar energy demand-to-supply management. This is because the user cannot install them infinitely, considering the available budget and installation area. Therefore, considering the cost of installing panels and batteries is required when conducting solar energy demand-to-supply management. Second, the applied demand-to-supply management method should be implemented throughout the entire supply chain process, including procurement, production, and retail facilities. This is because the target facility in this study was the distribution center with only delivered food. The third direction of future research involves analyzing the differences in GHGs generated by purchased electricity over a specific timeframe, such as a month or season, using the results of this study. The fourth direction of future study involves evaluating the cost of installing an appropriate scale of panels and batteries for solar energy demand-to-supply management with consideration of the grid electricity price. This is because considering and varying grid electricity prices are helpful for solar-energy demand-to-supply management.

Author Contributions: A.T., H.I. and T.Y. conceptualized the goals and the aims of this study. A.T., H.I., M.M. and T.Y. designed the methodology. A.T. wrote the original draft assisted by H.I. and H.I. and T.Y. shaped this manuscript based on the original draft. T.Y. acquired funds. A.T. applied formulations, programmed and validated the formulation, and visualized the results with H.I., T.Y. and A.T. conducted the numerical experiment, and H.I. and T.Y. reviewed it. T.Y. and H.I. managed this project and supervised the overall content. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A.1. Calculation of the Power Purchase Amount in Period t, P_t Using Conventional Purchasing Method for the Supply Shortage in Section 5.3

Power purchase amount in period t, P_t is calculated as shown in Equation (A1) when the conventional purchasing method for the supply shortage is applied.

$$P_t = \begin{cases} O_t - S_t - L_{init}(t = 0) \\ O_t - S_t - L_{t-1}(t \geq 1) \end{cases} \tag{A1}$$

Appendix A.2. Feedback

We received feedback from the staff of Ecolomy Co., Ltd. regarding the results of Chapter 4. The applicability and possibility of this study are investigated based on the feedback as follows:

- We received a comment regarding the decision to install batteries for a company. They described that "The decision on whether or not to install batteries is made first, and then the storage capacity is considered in a company. Therefore, a company will be more willing to install batteries if the effectiveness of the proposed method can be demonstrated in case which the amount of solar power generation is larger than that of power consumption at many times".
- We also received a positive opinion regarding the application of the on-demand cumulative control method and conducting solar power dynamic demand-to-supply management. They evaluated that "The case of conducting solar power dynamic demand-to-supply management for each time by using proposed method is not widely used. However, the cost of electricity has been more expensive, and the view of rising the cost of electricity becomes more severe for companies." This feedback means that the method proposed in this study is useful and solar power dynamic demand-to-supply management has the potential to be helpful in actual workspaces in the future.

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