Techno-Economic Analysis of Factory Energy Management with Market Price Spread between Electricity and Gas under Take-or-Pay Contract

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***Abstract*—Energy transition in the industrial sector is essential to achieve carbon neutrality by 2050. This paper develops a factory energy management system to optimize the procurement and operation of the cogeneration systems under electricity and gas retail contracts. While take-or-pay gas contracts are commonly used to stabilize fuel consumption, there is a trade-off between flexible demand response and constrained energy usage. The developed factory energy management system minimizes the total energy cost by leveraging the market price spread between grid electricity and natural gas. Through the techno-economic analysis, the impact of relaxing take-or-pay constraints on operational flexibility is evaluated. The results demonstrate that the developed factory energy management system effectively reduces the total annual energy cost and mitigates monthly cost volatility by synergistically utilizing both energy sources.**

***Index Terms*—Factory Energy Management System, Demand Response, Cogeneration, Electricity Market, Gas Market**

I. Introduction

Toward achieving carbon neutrality by 2050, advanced energy management in industrial facilities is increasingly critical, such as in factories [1], [2], local distributed energy resources [3], [4], and EV public transports [5], [6]. As renewable energy integration and market developments grow, energy management systems that utilize distributed energy resources as a demand response [7], [8] can reduce energy costs, mitigate price fluctuation risks [9], and improve renewable energy utilization for industrial facilities.

Industrial facilities increasingly procure both electricity and gas through market-based trading. While wholesale electricity prices fluctuate rapidly, retail gas prices have a delayed response to market changes due to fuel cost adjustment mechanisms. By exploiting this temporal price lag, dual-energy consumers can strategically adjust their electricity and gas consumption to reduce overall energy costs and hedge against monthly price volatility.

A factory energy management system must satisfy strict physical constraints, including continuous electricity and steam supply-demand balances. Traditionally, large factories rely entirely on purchased gas to meet these demands using gas-engine cogeneration systems and supplementary gas boilers. Previous studies have successfully reduced energy costs by implementing demand response, which increases net grid electricity demand by lowering gas engine outputs during periods of renewable energy surplus and low electricity prices [10], [11].

However, industrial gas retail contracts frequently include a take-or-pay clause, enforcing a strict lower limit on annual gas purchases. Although important contributions have been made to factory energy management systems, the take-or-pay constraint is not taken into account in these previous studies, and its impact is not analyzed. In this paper, the developed approach enables the reduction of monthly cost fluctuation risks by exploiting retail price differences, and analyzes how take-or-pay constraints affect the total energy cost within the developed factory energy management system.

The contributions of this paper are as follows.

- The developed factory energy management system provides the mitigation of energy cost volatility that reduces the fluctuation risk of monthly energy costs for industrial facilities by utilizing both electricity and gas.
- The techno-economic analysis of the gas retail contract is conducted to evaluate how the take-or-pay constraints affect the total annual energy costs of the industrial facilities.

II. Problem formulation

Industrial facilities typically require both electrical and thermal energy, such as steam, to maintain their continuous production processes. To satisfy these intensive energy demands efficiently, many factories install gas-engine cogeneration systems and gas boilers. These on-site generators provide flexibility in energy procurement, allowing the facility to choose between generating electricity locally by consuming natural gas or purchasing electricity directly from the power grid.

Fig. 1 illustrates the overview of the factory energy management system considered in this paper. The facility is interconnected with both the external electricity grid and the city gas network. The gas engines produce both electricity and steam simultaneously, while the gas boiler generates supplementary steam to fulfill the remaining thermal demand.

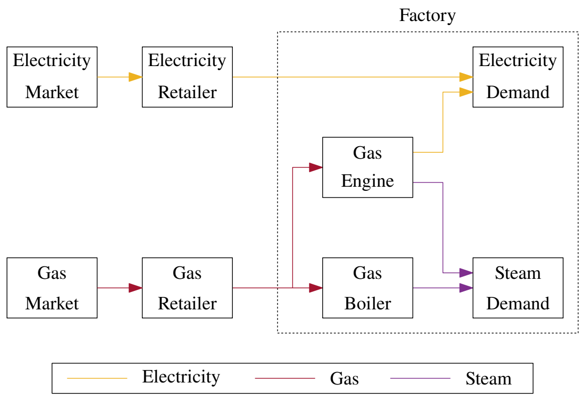

Fig. 1. Overview of factory energy management system. The factory purchase the electricity and gas from the retailers. The retailers purchase the electricity and gas from the market. The retail price is linked to the market price, including the selling and administrative expenses.

While prioritizing the use of cheap grid electricity during the solar power surplus hours can reduce short-term costs but it might violate the gas take-or-pay constraint that is the required minimum annual consumption. The scheduling leverages the temporal price spreads between the electricity and gas markets while strictly adhering to the complex physical and contractual boundaries.

To achieve this, the factory energy management system needs to satisfy the following requirements.

- The developed system maintains both the electricity and steam supply-demand balances in industrial facilities.
- The annual energy cost is minimized by the optimal operation of the gas engines, the gas boiler, and the purchased electricity under the gas take-or-pay constraint.

III. Approach

This section presents the optimization problem formulation of the developed factory energy management system. Let $\mathcal{T} = \{1, \ldots, T\}$ be the set of time indices in the scheduling horizon, and let $\mathcal{K} = \{1, 2\}$ denote the set of gas engines.

A. Objective function

The objective of the developed factory energy management system is to minimize the total energy cost over the scheduling horizon. The objective function J [JPY] of the total cost from purchasing electricity and gas is formulated as follows.

$$J = \sum_{t=1}^{T} (P_t^{\text{buy}} C_t^{\text{buy}} + G_t C_t^{\text{gas}}) \Delta t, \tag{1}$$

where P_t^{buy} [kW] and C_t^{buy} [JPY/kWh] are the purchased electricity and its unit price. The total gas consumption of the facility G_t [Nm^3/h] is given by

$$G_t = \sum_{k \in \mathcal{K}} G_{k,t}^{\text{GE}} + G_t^{\text{GB}} \quad \forall t \in \mathcal{T}, \tag{2}$$

where $G_{k,t}^{\text{GE}}$ [Nm^3/h] and G_t^{GB} [Nm^3/h] are the gas consumption of gas engine k and the gas boiler. C_t^{gas} [JPY/Nm^3] is the unit price of consumed gas. Δt [h] is the duration of each time step.

B. Power supply and demand balance

To ensure the stability of the facility's power system, the total electricity supply must continuously match the total electricity demand. This balance constraint is given by

$$D_t^{\text{elec}} = P_t^{\text{buy}} + \sum_{k \in \mathcal{K}} P_{k,t}^{\text{GE}} \quad \forall t \in \mathcal{T}, \tag{3}$$

where D_t^{elec} [kW] is the electricity demand of the facility. $P_{k,t}^{\text{GE}}$ [kW] is the power output of gas engine k.

C. Steam supply and demand balance

Similarly, the facility's steam demand must be satisfied by the combined steam generation from the gas engines and the gas boiler. The steam output from the gas engines is modeled as a constant value while the units are in operation that is given by

$$D_t^{\text{steam}} = S_t^{\text{GB}} + S_{\text{const}}^{\text{GE}} \sum_{k \in \mathcal{K}} u_{k,t}^{\text{GE}} \quad \forall t \in \mathcal{T}, \tag{4}$$

where D_t^{steam} [t/h] is the steam demand. $S_{\text{const}}^{\text{GE}}$ [t/h] is the constant steam production rate of the gas engines during operation. $u_{k,t}^{\text{GE}} \in \{0, 1\}$ is the binary commitment status of gas engine k that is 1 if operating and 0 otherwise. S_t^{GB} [t/h] is the steam output of the gas boiler.

D. Equipment specification

The power output characteristics of the gas engines are modeled linearly with respect to their gas consumption. The operational limits are bounded by semi-continuous constraints to reflect the minimum and maximum capacity as follows.

$$P_{k,t}^{\text{GE}} = \alpha G_{k,t}^{\text{GE}} - \beta u_{k,t}^{\text{GE}} \quad \forall k \in \mathcal{K}, \forall t \in \mathcal{T}, \tag{5}$$

$$G_{\min}^{\text{GE}} u_{k,t}^{\text{GE}} \le G_{k,t}^{\text{GE}} \le G_{\max}^{\text{GE}} u_{k,t}^{\text{GE}} \quad \forall k \in \mathcal{K}, \forall t \in \mathcal{T}, \tag{6}$$

$$P_{\min}^{\text{GE}} u_{k,t}^{\text{GE}} \le P_{k,t}^{\text{GE}} \le P_{\max}^{\text{GE}} u_{k,t}^{\text{GE}} \quad \forall k \in \mathcal{K}, \forall t \in \mathcal{T}, \tag{7}$$

where α and β are the performance coefficients of the gas engines. $G_{\min}^{\text{GE}}$ [Nm^3/h] and $G_{\max}^{\text{GE}}$ [Nm^3/h] are the minimum and maximum limits of gas consumption, respectively. $P_{\min}^{\text{GE}}$ [kW] and $P_{\max}^{\text{GE}}$ [kW] are the minimum and maximum power outputs, respectively. The steam production of the gas boiler is modeled proportionally to its gas consumption as follows.

$$S_t^{\text{GB}} = \eta^{\text{GB}} G_t^{\text{GB}} \quad \forall t \in \mathcal{T}, \tag{8}$$

where η^{GB} [t/Nm^3] is the conversion efficiency of the gas boiler.

TABLE I
PARAMETERS OF GAS ENGINE AND GAS BOILER.

Component	Parameter	Symbol	Value
Gas Engine	Number of units	$\lvert\mathcal{K}\rvert$	2
	Min. power output	$P^{\mathrm{GE}}_{\mathrm{min}}$	$4000\,\mathrm{kW}$
	Max. power output	$P^{\mathrm{GE}}_{\mathrm{max}}$	$8000\,\mathrm{kW}$
	Min. gas consumption	$G^{\mathrm{GE}}_{\mathrm{min}}$	$780\,\mathrm{Nm^3/h}$
	Max. gas consumption	$G^{\mathrm{GE}}_{\mathrm{max}}$	$1500\,\mathrm{Nm^3/h}$
	Slope coefficient	α	50/9
	Intercept coefficient	β	1000/3
	Constant steam output	$S^{\mathrm{GE}}_{\mathrm{const}}$	$3.0\,\mathrm{t/h}$
Gas Boiler	Conversion efficiency	η^{GB}	$0.016\,\mathrm{t/Nm^3}$

E. Take-or-pay constraint

In industrial energy procurement, gas purchasing contracts often include a take-or-pay clause, which requires the facility to consume a minimum volume of gas over a specific period. To model this contractual requirement, a take-or-pay constraint is introduced. This constraint ensures that the total gas consumption over the entire scheduling horizon meets or exceeds a predefined lower limit. The lower limit is defined as a certain proportion of a baseline gas consumption.

$$\sum_{t=1}^{T} G_t \Delta t \geq \gamma^{\mathrm{ToP}} G_{\mathrm{base}}, \tag{9}$$

where γ^{ToP} is the take-or-pay ratio parameter representing the minimum required proportion of the baseline gas consumption. G_{base} $[\mathrm{Nm^3}]$ is the baseline total gas consumption over the scheduling horizon. The baseline gas consumption G_{base} is a constant parameter estimated a priori under the assumption that the facility satisfies all of its electricity and steam demands solely through the operation of its own gas engines and gas boiler, without purchasing any electricity from the power grid.

F. Optimization problem formulation

By integrating the objective function and constraints, the optimization problem of the factory energy management system is formulated as a Mixed-Integer Linear Programming (MILP) model that is given by

$$\begin{aligned} \min \quad & \text{Eq. (1)} \\ \text{subject to} \quad & \text{Eqs. (2)–(9)} \\ & P^{\mathrm{buy}}_t, P^{\mathrm{GE}}_{k,t}, G^{\mathrm{GE}}_{k,t}, G^{\mathrm{GB}}_t \geq 0 \\ & u^{\mathrm{GE}}_{k,t} \in \{0,1\} \\ & \forall k \in \mathcal{K}, \forall t \in \mathcal{T} \end{aligned}$$

The objective function J, defined in Eq. (1), is minimized while strictly satisfying the constraints from Eqs. (2) to (9), along with the non-negativity constraints for all continuous variables. Since this formulation consists entirely of linear equations and inequalities involving continuous and binary variables, the problem can be efficiently solved to global optimality using MILP solvers.

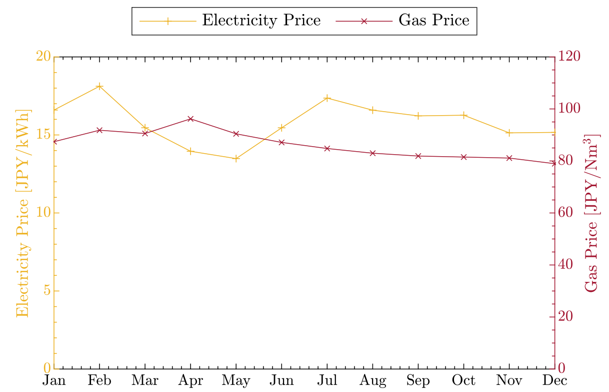

Fig. 2. Monthly average retail price of electricity and gas. The gas retail price has a three-month delay from the imported gas price in the trade statistics data.

IV. VALIDATION

A. Conditions

The numerical simulation to evaluate the developed model of the factory energy management system is conducted over a year period from January 1 to December 31 in 2025. The scheduling horizon is configured with a time step of $\Delta t = 0.5\,\mathrm{h}$ $(30\,\mathrm{min})$. Consequently, the total number of time steps T is $17\,520$ $(= 365 \times 24 \times 2)$. To evaluate the effectiveness of the developed model, a numerical simulation is conducted based on a representative industrial facility.

1) Electricity and steam demand: To clearly evaluate the impact of market price volatility on the total operational cost and to isolate the effects of the developed coordinated procurement strategy, the energy requirements of the industrial facility are assumed to be constant throughout the entire scheduling horizon. Specifically, the electricity demand D^{elec}_t is strictly fixed at $16\,000\,\mathrm{kW}$ for all time steps $t \in \mathcal{T}$. Similarly, the steam demand D^{steam}_t is maintained at a constant rate of $20\,\mathrm{t/h}$ for all $t \in \mathcal{T}$.

2) Gas engine and gas boiler: The specific technical parameters of the gas engine and the gas boiler are summarized in TABLE I. The facility is equipped with two identical gas engines $(\lvert\mathcal{K}\rvert = 2)$, each having a maximum power output of $8000\,\mathrm{kW}$. The slope coefficient α and intercept coefficient β of the gas engines are given by

$$\alpha = (P^{\mathrm{GE}}_{\mathrm{max}} - P^{\mathrm{GE}}_{\mathrm{min}})/(G^{\mathrm{GE}}_{\mathrm{max}} - G^{\mathrm{GE}}_{\mathrm{min}}), \tag{10}$$

$$\beta = (P^{\mathrm{GE}}_{\mathrm{max}} G^{\mathrm{GE}}_{\mathrm{min}} - P^{\mathrm{GE}}_{\mathrm{min}} G^{\mathrm{GE}}_{\mathrm{max}})/(G^{\mathrm{GE}}_{\mathrm{max}} - G^{\mathrm{GE}}_{\mathrm{min}}), \tag{11}$$

where the power output characteristics are modeled as linear, and are set to $\alpha = 50/9$ and $\beta = 1000/3$. The constant steam production rate $S^{\mathrm{GE}}_{\mathrm{const}}$ during the gas engine operation is set to $3.0\,\mathrm{t/h}$. For the gas boiler, the conversion efficiency η^{GB} is set to $0.016\,\mathrm{t/Nm^3}$. To enforce the take-or-pay ratio is set to $\gamma^{\mathrm{ToP}} = 1, 0.9, 0$ in three scenarios, respectively.

3) Electricity retail price: The electricity purchasing price C^{buy}_t $[\mathrm{JPY/kWh}]$ is modeled as a dynamic pricing structure linked to the spot market of the Japan Electric Power eX-

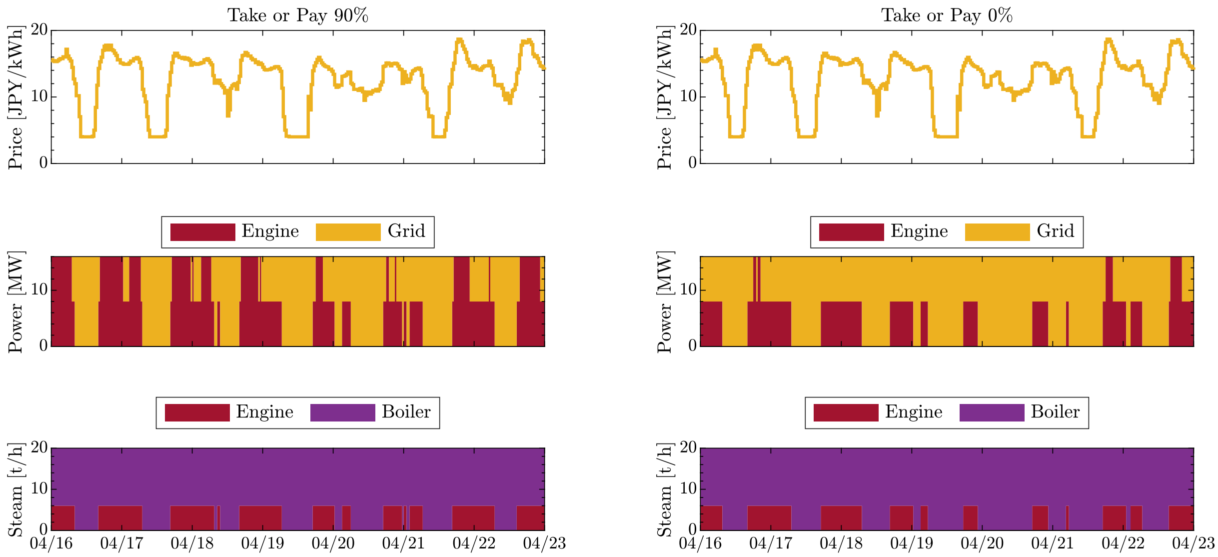

Fig. 3. Balance of electricity and steam from 16 to 22 April, 2025. Left: optimization results with the take-or-pay ratio $\gamma_{ToP} = 0.9$ (90 %). Right: optimization results with the take-or-pay ratio $\gamma_{ToP} = 0$ (0 %). Top: electricity retail price. Middle: electricity balance. Bottom: steam balance. When the take-or-pay ratio is $\gamma_{ToP} = 1$ (100 %), the electricity is fully supplied by the generator with the constant steam supply. The rest of the steam is supplied by the gas boiler.

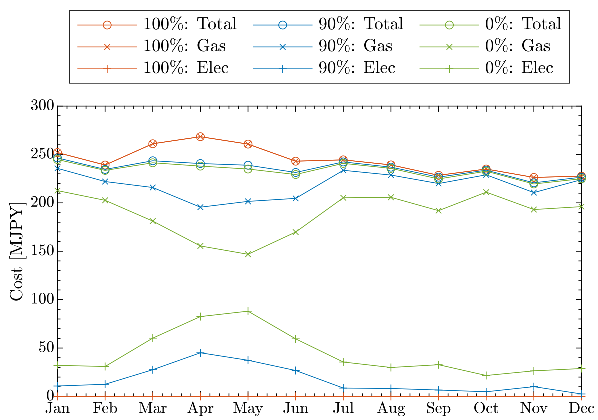

Fig. 4. Monthly energy costs in each take-or-pay ratio $\gamma_{ToP} = 1$ (100 %), 0.9 (90 %), and 0 (0 %).

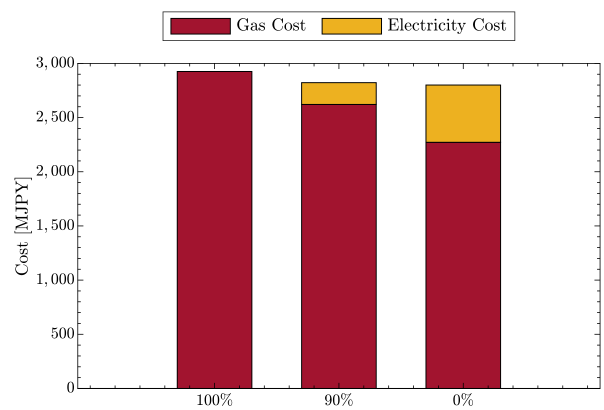

Fig. 5. Annual energy costs in each take-or-pay ratio $\gamma_{ToP} = 1$ (100 %), 0.9 (90 %), and 0 (0 %).

change (JEPX) [12]. The unit price of purchased electricity is formulated as follows.

$$C_t^{\text{buy}} = \frac{C_t^{\text{JEPX}}}{1 - l^{\text{grid}}} + C^{\text{grid}} + C_t^{\text{res}}, \tag{12}$$

where C_t^{JEPX} [JPY/kWh] is the JEPX system price. The grid loss rate is set to $l^{\text{grid}} = 0.013$ (1.3 %). The wheeling charge is set to $C^{\text{grid}} = 0.827\,\text{JPY/kWh}$ excluding tax. The renewable energy surcharge C_t^{res} [JPY/kWh] is specified as $3.17\,\text{JPY/kWh}$ from January 1 to April 30, and $3.62\,\text{JPY/kWh}$ from May 1 to December 31, 2025, both excluding tax.

4) Gas retail price: The gas retail price C_t^{gas} [JPY/Nm^3] is determined based on the Trade Statistics of Japan [13]. The raw data provides the actual import price of Liquefied Natural Gas (LNG), denoted as C^{LNG} [JPY/MT], where 1 MT is equivalent to 1000 kg. Assuming the total heating value of 1 MT of LNG is approximately 54 000 MJ and the Lower Heating Value (LHV) of standard city gas is 45 MJ/Nm^3, the volumetric equivalent of 1 MT is calculated as $54000/45 = 1200$ Nm^3. Therefore, the basic unit conversion for the gas price is formulated as follows.

$$C_{\text{base}}^{\text{gas}} = \frac{C^{\text{LNG}}}{1200}, \tag{13}$$

where $C_{\text{base}}^{\text{gas}}$ [JPY/Nm^3] represents the base volumetric import price. To reflect the time lag inherent in the fuel cost adjustment mechanism, the final gas retail price C_t^{gas} for a specific month is calculated by applying a three-month delay to this volumetric import price $C_{\text{base}}^{\text{gas}}$ and multiplying it by a predefined coefficient 1.15 that reflects the selling and administrative expenses. Consequently, the historical trade

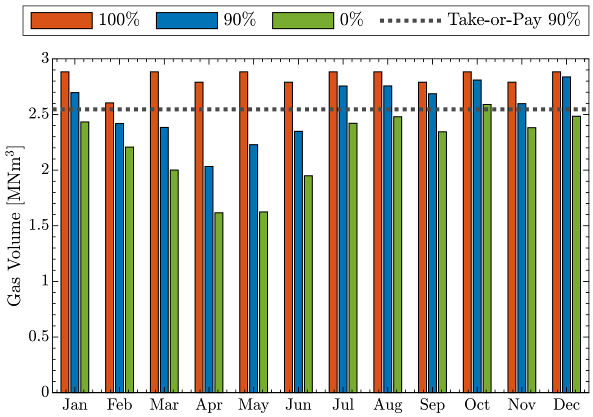

Fig. 6. Monthly gas volume in each take-or-pay ratio $\gamma_{ToP} = 1$ (100 %), 0.9 (90 %), and 0 (0 %). The horizontal black dotted line shows the monthly averaged take-or-pay lower limit with take-or-pay ratio $\gamma_{ToP} = 0.9$ (90 %) as a reference. Note that this monthly lower limit is not necessarily satisfied.

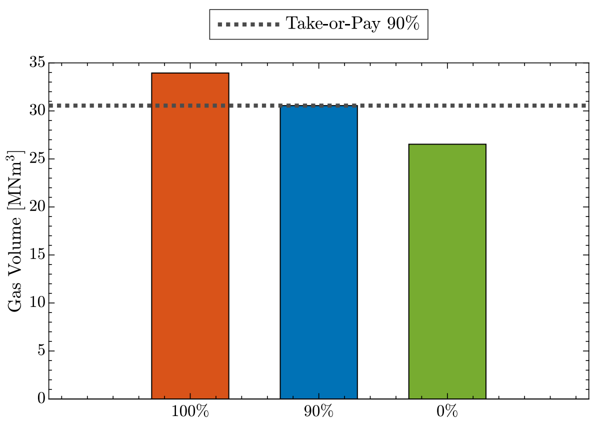

Fig. 7. Annual gas volume in each take-or-pay ratio $\gamma_{ToP} = 1$ (100 %), 0.9 (90 %), and 0 (0 %). The horizontal black dotted line shows the annual take-or-pay lower limit with take-or-pay ratio $\gamma_{ToP} = 0.9$ (90 %).

statistics data from October 2024 to September 2025 are utilized to derive the applicable monthly gas prices for the simulation period from January to December 2025. It should be noted that the gas retail price C_t^{gas} remains constant across all time steps t within each respective month.

B. Optimization Results

In this paper, three scenarios are investigated in the different take-or-pay ratio $\gamma_{ToP} = 1$ (100 %), 0.9 (90 %), and 0 (0 %).

Fig. 2 shows the monthly average retail prices of electricity and gas. The gas retail price exhibits a three-month delay compared to the import trade statistics due to the fuel cost adjustment mechanism. In contrast, the electricity market price drops significantly around April and May due to the curtailment of solar power generation. Monthly cost volatility can be hedged by selectively utilizing the cheaper energy source based on these temporal price differences.

Fig. 3 illustrates the energy balance from April 16 to 22 in 2025, to investigate short-term operational behavior. During daytime due to curtailment of the solar power generation, the spot market price frequently drops to $0.01\ \mathrm{JPY/kWh}$. During these periods, the factory energy management system strategically shuts down the gas engines, purchases grid electricity, and increases boiler output to meet the constant steam demand. Under $\gamma^{\mathrm{ToP}} = 0.9$, the system effectively captures these low-price windows. When $\gamma^{\mathrm{ToP}} = 0$, grid purchases expand even to relatively higher-price periods. Note that the facility relies entirely on continuous gas engine operation when $\gamma^{\mathrm{ToP}} = 1$.

Fig. 4 and Fig. 5 show the monthly and annual energy cost, respectively. Under $\gamma^{\mathrm{ToP}} = 1$, the energy costs directly follow the fluctuations in the gas import price. Relaxing the constraint to $\gamma^{\mathrm{ToP}} = 0.9$ increases electricity procurement during the low-price months around April and May, which significantly reduces both the total annual costs and the monthly volatility. Further relaxation to $\gamma^{\mathrm{ToP}} = 0$ extends electricity purchasing from February to July. However, the cost reduction achieved from $\gamma^{\mathrm{ToP}} = 0.9$ to 0 is notably smaller than that from $\gamma^{\mathrm{ToP}} = 1$ to 0.9.

Fig. 6 and Fig. 7 show the monthly and annual gas volume, respectively. At $\gamma^{\mathrm{ToP}} = 1$, the annual gas volume reaches its maximum, while at $\gamma^{\mathrm{ToP}} = 0.9$, the total volume exactly binds to the contractual lower limit. Removing the take-or-pay constraint as $\gamma^{\mathrm{ToP}} = 0$ doubles the gas reduction compared to the shift from 1 to 0.9, with monthly volumes falling below the reference average limit for most of the year.

From these results, relaxing the take-or-pay constraint allows industrial facilities to actively leverage electricity market volatility to reduce total energy costs and hedge against market risks. A moderate take-or-pay ratio of approximately 0.8 may yield economic benefits nearly equivalent to having no constraint as $\gamma^{\mathrm{ToP}} = 0$. However, excessive relaxation increases reliance on the power grid. Since the Japanese power grid heavily relies on gas-fired thermal generation during non-solar hours, such an aggressive shift toward grid electricity may limit the potential for CO_2 emission reductions.

V. Conclusion

In this paper, the factory energy management system is developed to optimally coordinate the procurement and operation of distributed energy resources. The developed factory energy management system effectively reduces the total annual energy cost and mitigates the monthly cost volatility by synergistically utilizing both grid electricity and natural gas. The techno-economic analysis demonstrates that relaxing the take-or-pay constraint in gas purchasing contracts can potentially increase the utilization ratio of grid electricity. However, this electricity utilization ratio heavily depends on the relative pricing between electricity and gas as well as the potential for CO_2 emission reductions, indicating that completely eliminating the take-or-pay constraint is not strictly necessary to minimize the total energy cost. Ongoing research focuses on investigating advanced facility configurations capable of selling surplus electricity to the power grid and comprehensive analyses of energy cost risk hedging over multi-year horizons.

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