【*Technical Paper*】

FORMULATION OF A HIGHLY EXPLAINABLE MPC AND VERIFICATION BY ENERGY SIMULATION

Masanori Takahashi[1], Yuki Matsunami[1], Takuji Nakata[1], Kenichiro Katayama[1]

ABSTRACT

In this study, we aim to develop an Energy Management System (EMS) that uses model predictive control (MPC) to optimize photovoltaic and battery energy storage systems. In previous studies, we proposed an MPC formulation method based on mathematical optimization to address underlying issues. However, we identified additional issues related to the requirement for specialized expertise and inherent challenges in operational explanation and troubleshooting, which limit practical applicability. In this paper, we propose a novel control methodology based on a relatively simplified logic. In addition, we conducted case studies to compare its performance with conventional control strategies. Our simulation results showed that, when compared to a strategy that maximizes energy self-sufficiency, our method reduces annual electricity costs by approximately 20% and nearly half the simplified payback period. Furthermore, the evaluation indicators show that our proposed methodology performs similarly to that of a mathematical optimization control method.

1. INTRODUCTION

In this research, we aim to develop an energy management system (EMS) to maximize on-site renewable energy utilization and mitigate power supply from the grid. The operational objectives and evaluation indicators for equipment management differ according to each building, and stable operation requires consideration of equipment constraints and operational planning extending several days ahead. To address these issues, we have pursued the development of an EMS employing model predictive control (MPC) as an optimal control method.

Previous studies have reported various approaches to solving MPC optimization problems, including heuristic algorithms and mathematical optimization methods [1-5]. We have also reported an MPC formulation method applying mathematical optimization for power supply and demand control in a research facility, equipped with battery energy storage systems (BESS) and photovoltaics (PV) [2]. However, the application of mathematical optimization methods entails a need for specialized expertise and practice. Also, challenges remain regarding the difficulty of explaining system operations and investigating malfunctions. These factors may present both physical and psychological barriers to EMS deployment.

In this paper, we describe an initiative to formulate a more highly explainable MPC using a relatively simplified logic, with objectives of levelling grid power and enhancing energy self-sufficiency. The proposed control method, hereafter, is referred to as peak-cut control.

2. TARGET SYSTEM AND ENERGY SIMULATION

2.1 Overview of Energy System

In this report, system of Takasago Innovation Center (TIC) [1] was selected as the target for analysis. Main characteristics of the facility is shown in **Table 1**. The building is composed of an office, a laboratory and an equipment exhibition building. Regarding the purpose of this research, we focused exclusively on the office building.

This article is update of “International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2025)”, November 29 - December 2, 2025, Tokyo, JP

[1] Research & Development Center, Research & Development Headquarters, Takasago Thermal Engineering Co., Ltd.

Table 1 Facility overview

Location	Tsukubamirai-shi, Ibaraki-ken, Japan
Site Area	22,746 m^2
Total Floor Area	11,764 m^2 Office: 4,897 m^2 Laboratory: 6,058 m^2 Equipment exhibition: 809 m^2
Building Height	15.455 m (2-story)
Structure	Steel structure (partially reinforced concrete structure)
Completion	January 2020

Fig. 1 illustrates a schematic diagram of the target system's power configuration. Within TIC, photovoltaic (PV) systems are installed on the laboratory building rooftop, and large-capacity battery energy storage systems (BESS) are deployed both on the office building rooftop and site premises. However, in this report, only the office building is considered as the target of analysis. Therefore, BESS capacity is determined based on the office building's power demand, and PV capacity is determined from available rooftop area. The simulation conditions are summarized in **Table 2**. Notably, the simulation assumes that surplus electricity can be exported to the grid through reverse power flow.

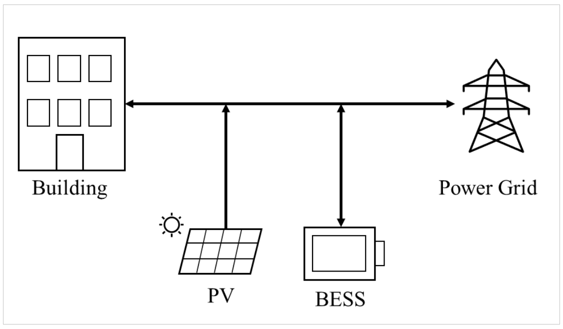

Fig. 1 Energy system diagram

Table 2 Simulation conditions

Target period	2024/1/1-2024/12/31
Annual power load	22,3403 kWh (max.117 kW)
PV rated output	60 kW
BESS rated capacity	400 kWh (C-rate50%)
BESS rated output	200 kW
Prediction period	24 h (per 1 h)
Time step	1 h

2.2 Power Load of TIC

The annual power load of the office building is shown in **Fig. 2**, and weekly load with the highest peak is shown in **Fig. 3** (August 17–23). Throughout the year, power demand peaks during the summer and winter seasons, reaching its lowest levels during the intermediate periods. Within the selected week, load decrease is observed on weekends, with pronounced peaks occurring during daytime hours of weekdays. These patterns show that the office building has typical load fluctuations for standard offices.

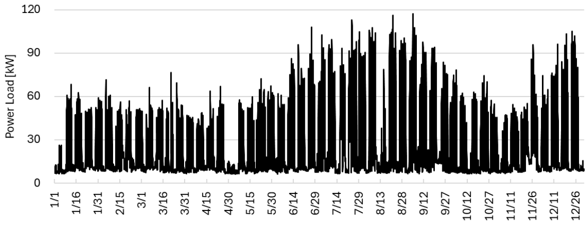

Fig. 2 Annual power load (2024/1/1-12/31)

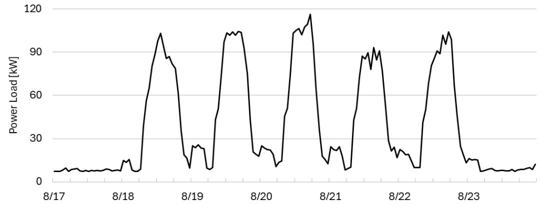

Fig. 3 Power load at 2024/8/17-8/23

2.3 Energy Simulation Flow

The flow chart of the energy simulation is shown in **Fig. 4**. First, the PV output is calculated using the specified solar irradiation data. Next, both the PV output and power load are used to determine the grid power target so that the operational constraints of BESS are met. Finally, values for BESS output, state of charge, and grid power are calculated. While MPC typically forecasts solar irradiation and power load from given conditions, this simulation assumes perfect prediction accuracy by utilizing actual measurement data from the office building. The PV and BESS models employed in this simulation are formulated based on methods proposed in a previous report [2].

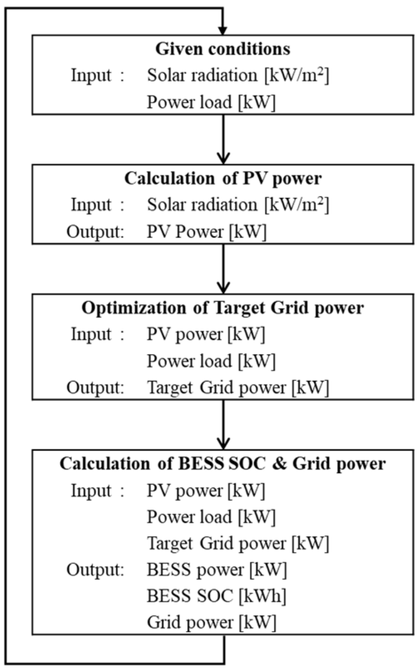

Fig. 4 Flow chart of energy simulation

2.4 Energy simulation flow

This subsection describes the methodology of the proposed peak cut control in this report. Additionally, the two control methods adopted for comparison is described: the energy self-sufficiency maximization control and the peak cut control using mathematical optimization.

2.4.1 Common constraints for all control methods

The general constraints applicable to all control methods are specified in equations (1) and (2). These constraints specify that both the output power and state of charge for BESS must remain within their respective rated minimum and maximum values.

$$P_{BESS\_min} \le \hat{P}_{BESS,k} \le P_{BESS\_max} \tag{1}$$

$$E_{BESS\_min} \le \hat{E}_{BESS,k} \le E_{BESS\_max} \tag{2}$$

($\hat{P}_{BESS,k}$: Predicted BESS power [kW], P_{BESS_min}: Minimum BESS power [kW], P_{BESS_max}: Maximum BESS power [kW], $\hat{E}_{BESS,k}$: Predicted BESS SOC [kWh], E_{BESS_min}: Minimum BESS SOC [kWh], E_{BESS_max}: Maximum BESS SOC [kWh])

2.4.2 Energy self-sufficiency maximization control (Basic method)

This method is designed to store surplus power generated by PV and, in response to power demand, preferentially supply the stored energy from BESS [2]. The calculation method of BESS output is showen in equation (3).

$$P_{BESS,t} = P_{load,t} - P_{PV,t} \tag{3}$$

(t: Target time for control, $P_{BESS,t}$: BESS power [kW], $P_{load,t}$: Power load [kW], $P_{PV,t}$: PV power [kW])

2.4.3 Proposed peak cut control (Proposed method)

Based on the proposed method, equations for determining target values of grid power are shown in equations (4) to (8). In this approach, two thresholds are introduced: P_{thr_max}, which is designed to suppress the peak of grid power, and P_{thr_min}, which is utilized to elevate the minimum value of grid power by pre-charging BESS.

$$0 \leq P_{thr\_max} \leq P_{demand} \tag{4}$$

$$0 \leq P_{thr\_min} \leq P_{demand} \tag{5}$$

$$\hat{\mathbf{P}}_{grid\_basic} = \hat{\mathbf{P}}_{load} - \hat{\mathbf{P}}_{PV} \tag{6}$$

$$\hat{P}_{grid\_opt,k} = \begin{cases} P_{thr\_max}, & P_{thr\_max} < \hat{P}_{grid\_basic,k} \\ \hat{P}_{grid\_basic,k}, & P_{thr\_min} \leq \hat{P}_{grid\_basic,k} \leq P_{thr\_max} \\ P_{thr\_min}, & \hat{P}_{grid\_basic,k} < P_{thr\_min} \end{cases} \tag{7}$$

$$minimize\ f_{obj1} = \max(\hat{\mathbf{P}}_{grid\_opt}) \tag{8}$$

($\hat{\mathbf{P}}_{grid\_basic}$: Predicted grid power during the prediction period based on basic method [kW], $\hat{\mathbf{P}}_{load}$: Predicted power load during the prediction period [kW], $\hat{\mathbf{P}}_{PV}$: Predicted PV power during the prediction period [kW], $\hat{P}_{grid\_opt,k}$: Target value of grid power [kW], $\hat{P}_{grid\_basic,k}$: Predicted grid power based on basic method [kW], f_{obj1}: Objective function of proposed method, $\hat{\mathbf{P}}_{BESS}$: Predicted BESS power during the prediction period [kW])

The calculation procedure is outlined as follows. The threshold values, P_{thr_max} and P_{thr_min}, are each explored across the range from 0 kW to the demand power, divided into 20 segments.

1. Calculate the grid power based on basic method control ($\hat{\mathbf{P}}_{grid\_net}$), given the PV output and power load as input conditions.
2. Determine the target value of grid power using equation (7), from $\hat{\mathbf{P}}_{grid\_net}$ and the assumed values of P_{thr_max} and P_{thr_min}.
3. Run an energy simulation over the prediction period based on the target values of grid power determined in Step 2.
4. By repeating Steps 2 and 3, search for the optimal solution as the set of conditions that minimizes the objective function (f_{obj1}).

Fig. 5 shows a schematic of grid power and BESS SOC control results using the proposed method.

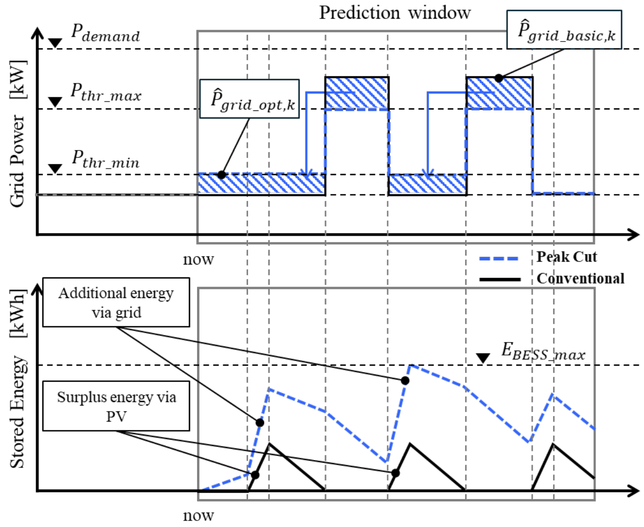

Fig. 5 Control results of grid power and BESS SOC

2.4.4 Peak cut control by mathematical optimization (SQP method)

The objective function of the SQP method is shown in Equations (9) and (10). The root mean square of the grid power is utilized to minimize both the total amount and the variance of grid power over the prediction period. To facilitate the convergence of the optimization calculation, grid power is normalized by dividing it by the maximum value of the power load (demand power).

$$minimize\ f_{obj2} = \sqrt{\sum_{k=0}^{T-1} \hat{w}_{grid,k}{}^2} \tag{9}$$

$$\hat{w}_{grid,k} = \frac{\hat{P}_{grid,k}}{P_{demand}} \tag{10}$$

(f_{obj2}: Objective function of SQP method, T: Number of prediction steps [-], k: Any number of steps within the prediction period [-], $\hat{w}_{grid,k}$: Normalized predicted grid power [-], $\hat{P}_{grid,k}$: Predicted grid power [kW], P_{demand}: Demand power [kW])

An algorithm based on Sequential Quadratic Programming (SQP) was adopted to solve the optimization problem. Specifically, the SLSQP solver from the Python library SciPy [6] was utilized. Furthermore, as SQP requires the use of differentiable expressions, a continuous approximation model for BESS, based on the method reported in a previous study [2], was employed to facilitate the optimization process.

2.5 Evaluation Method

The simulation results based on each control methods were evaluated based on the following indicators: electricity cost, CO_2 emission and payback period. These metrics were selected to provide a comprehensive assessment of the system's performance.

2.5.1 Electricity cost

The calculation equations for electricity cost are presented in Equations (11) to (13). The unit prices for electricity charges are based on a typical high-voltage pricing structure in Japan [7].

$$COST_{all} = COST_E + COST_P \tag{11}$$

$$COST_E = U_E\, E_{grid} \tag{12}$$

$$COST_P = 12\, U_P\, P_{grid\_max} \tag{13}$$

($COST_{all}$: Annual electricity cost [yen/year], $COST_E$: Annual electricity charge [yen/year], $COST_P$: Annual basic charge [yen/year], U_E: Electricity charge unit price [yen/kWh], E_{grid}: Annual amount of received grid power [kWh/year], U_P: Basic charge unit price [yen/kW·month], P_{grid_max}: Maximum annual grid power [kW])

2.5.2 CO_2 emissions

The calculation equations for CO_2 emissions are shown in Equation (14).

$$C_{carbon} = U_{carbon}\, E_{grid} \tag{14}$$

(C_{carbon}: annual CO_2 emission [t-CO_2/year], U_{carbon}: CO_2 emission coefficient [t-CO_2/kWh])

2.5.3 Simple payback period

The calculation equations for the simple payback period are presented in Equations (15) and (16). In this report, the simple payback period is defined as the equipment installation cost divided by the annual electricity cost reduction achieved. The reduction in electricity cost is calculated based on the annual electricity cost prior to the installation of equipment.

$$Y_{payback} = \frac{COST_{initial}}{COST_{reduced}} \tag{15}$$

$$COST_{reduced} = COST_{bare} - COST_{all} \tag{16}$$

($Y_{payback}$: Simple payback period [year], $COST_{initial}$: Equipment installation cost [yen], $COST_{reduced}$: Annual electricity costs reduced by equipment installation [yen/year], $COST_{bare}$: Annual electricity cost before installing equipment [yen/year])

The constant values adopted for each indicator are presented in **Table 3**. The electricity charges and the CO_2 emission coefficient are based on the published figures for fiscal year 2024 [7].

Table 3 Constant values used for each indicator

Electricity charge unit price	20.61	yen/kWh
Basic charge unit price	3,220	yen/kW·month
CO_2 emission coefficient	0.000434	t-CO_2/kWh
Equipment installation cost	34.2	Millions of yen
PV system unit price	170,000	yen/kW
BESS unit price	60,000	yen/kWh

3. CALCULATION RESULTS AND EVALUATION

3.1 Qualitative Evaluation of a Representative Week

Fig. 6–8 display the weekly profiles of power load, PV output, BESS power, and grid power for August 17–23, 2024, which had the highest load. With the Basic method, early depletion of BESS state of charge limits its discharge and causes higher daytime grid power peaks. In contrast, both the proposed and SQP methods optimize BESS usage, reducing grid power peaks to 40–60 kW. The similar patterns in BESS charge and grid power confirm the effectiveness of the proposed approach in peak reduction.

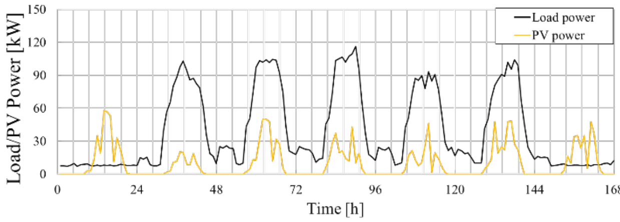

Fig. 6 Power load and PV generated power

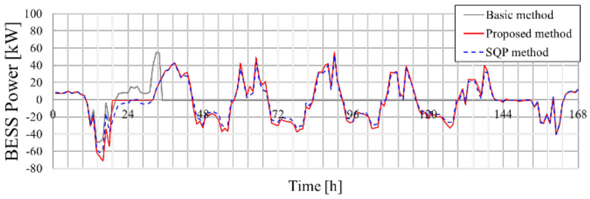

Fig. 7 Results of BESS power

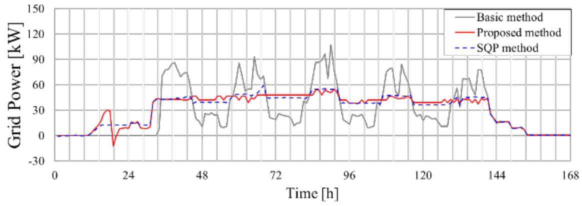

Fig. 8 Results of grid power

3.2 Quantitative Evaluation of Annual Simulation Results.

The evaluation indicators of electricity cost, CO_2 emissions, and simple payback period were calculated, and both the results and reduction rates were determined, respectively. The reduction rates for electricity cost and CO_2 emissions were calculated based on evaluation values prior to equipment installation, as well as the simple payback period.

3.2.1 Results of Electricity cost

The results for electricity cost and its reduction rate are presented in **Fig. 9 and 10**. Compared to the Basic method, both the proposed method and the SQP method resulted in a comparable decrease in electricity costs. Notably, the annual basic charge was reduced to approximately half, demonstrating a significant effect of the grid power levelling achieved by the methods. The cost reduction rate for both the proposed and SQP method was approximately 20%, indicating the pronounced impact of implementing peak-cut control. Although the proposed method and SQP method differ in specific electricity cost reductions, their overall reduction rates were overall the same.

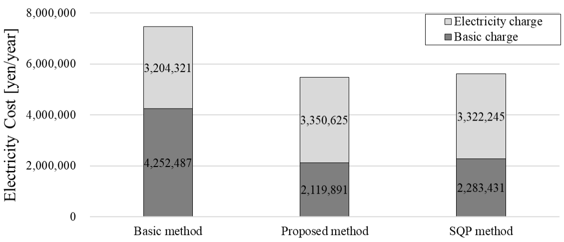

Fig. 9 Results of annual electricity cost

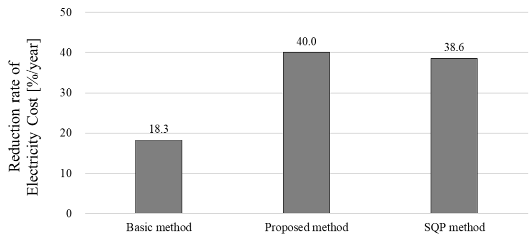

Fig. 10 Results of reduction rate for electricity cost

3.2.2 Results of CO_2 emissions

Fig. 11 and 12 show that all control methods reduced CO_2 emissions by about 30%, mainly due to PV's effect on lowering grid power usage. It also shows that both the proposed and SQP methods produced similar CO_2 emission outcomes.

On the other hand, compared to the Basic method, both the proposed and SQP methods slightly increased CO_2 emissions due to greater annual grid power usage from BESS charge/discharge losses (see

Fig. 13). This results from the increase in BESS cycles with the peak cut control versus Basic method. While further optimization of BESS operations could reduce CO_2 emissions, there is a trade-off between lowering electricity costs and CO_2 emissions. As PV and BESS adoption grows, it will be important to tailor solutions to each customer's needs.

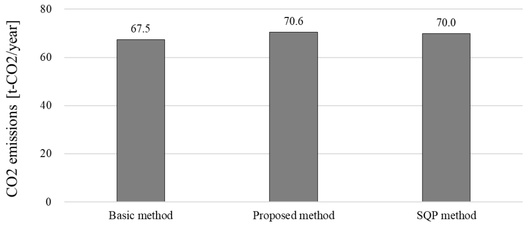

Fig. 11 Results of annual CO_2 emissions

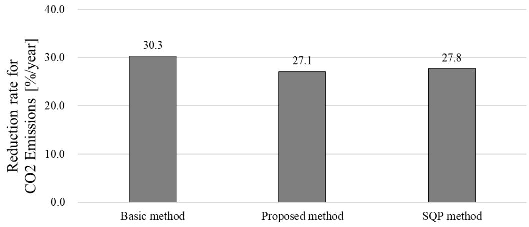

Fig. 12 Results of reduction rate for annual CO_2 emissions

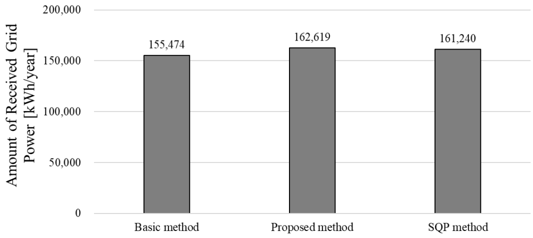

Fig. 13 Results of annual amount of received grid power

3.2.3 Results of Simple payback period

The results for the simple payback period are presented in **Fig. 14**. In comparison to the Basic method, both the proposed method and SQP method achieved a reduction in the payback period to approximately half. Furthermore, the evaluation results for the proposed method and SQP method were essentially equivalent.

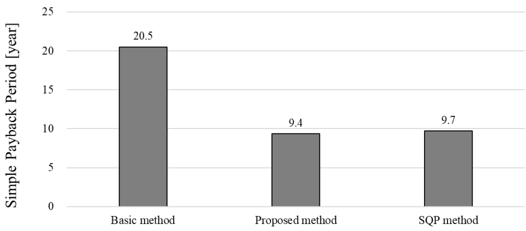

Fig. 14 Results of simple payback period

4. CONCLUSIONS

In this study, a control method for BESS with a relatively simplified logic was proposed for facilities equipped with PV and BESS, and its performance was compared with multiple control strategies through energy simulation. The findings for the proposed method are as follows.

1. Compared to the energy self-sufficiency maximization control, the proposed method achieved approximately a 20% improvement in annual electricity cost reduction rate and shortened the simple payback period to about half.
2. The annual CO_2 emissions reduction rate remained roughly equivalent at around 30% for all control strategies implemented.

3. The proposed method achieved the peak-cut control similar to that achieved through mathematical optimization method and resulted in evaluation values that were generally equivalent.

REFERENCES

[1] Matsunami, Y., Gao, Y., Miyata, S., Akashi, Y., Shibata, K., Katayama, K., and Hirahara, Y., “Development of a grid independent energy system using energy supply and demand prediction (Part 1) Concept and problem identification from operational data”, *Technical papers of annual meeting SHASEJ*, vol. 9, IS-8, (2021). **Conference Proceedings**

[2] Matsunami, Y., Miyata, S., Gao, Y., Kawakami, Y., Shibata, K., and Akashi, Y., “電力の変動料金制における建築エネルギーシステムの蓄電池モデル予測制御”, *Transactions of SHASEJ*, vol. 48, No. 315, pp. 29-39, (2023). **Journal Paper**

[3] Groß, A., Wittwer, C., and Diehl, M., “Stochastic model predictive control of photovoltaic battery systems using a probabilistic forecast model”, *European Journal of Control*, vol.56, pp. 254-264, (2020). **Journal Paper**

[4] Hou, J., Li, H., Nord, N., and Huang, G., “Model predictive control under weather forecast uncertainty for HVAC systems in university buildings”, *Energy and Buildings*, vol. 257, article 111793, (2022). **Journal Paper**

[5] Miyata, S., Kuwahara, Y., Lim, J., Akashi, Y., and Yoshimoto, N., “動的 CO_2 排出係数に基づいたモデル予測制御による熱源機器の低炭素制御”, *Transactions of AIJ. Journal of Environmental Engineering*, vol. 85, No. 777, pp. 827-835, (2020). **Journal Paper**

[6] The SciPy community, *SciPy documentation*, July 17, 2025, from https://docs.scipy.org/doc/scipy/reference/optimize.minimize-slsqp.html#optimize-minimize-slsqp. **Webpages: Nonperiodical Web Document**

[7] TEPCO Energy Partner, Inc., *Electricity rate plans for special high voltage and high voltage customers*, July 17, 2025, from https://www.tepco.co.jp/ep/corporate/plan_h/minaoshi_2025plan.html. **Webpages: Nonperiodical Web Document**

要　約

本研究では、太陽光発電設備や蓄電池システムを最適制御する手段として、モデル予測制御(MPC)を採用したエネルギーマネジメントシステムの開発を進めてきた。既往の研究で、最適化問題の解法に数理最適化を適用した MPC を提案したが、専門知識の必要性や動作説明・不具合調査の難しさなど実用面において課題がある。本研究では、比較的簡易なロジックを用いて定式化した制御手法を提案し、ケーススタディを実施して他の制御手法と比較した。シミュレーションの結果、エネルギー自給率を最大化する制御と比較して、年間電力コストが約 20%削減され、単純投資回収年数が約半分に短縮された。また、本研究で用いた評価指標において、数理最適化を適用した制御と概ね同等の性能を確認できた。