Analysis on the Location Selection and Operational Flexibility of Electricity-Consuming Facilities: A Perspective of Power System Cost Minimization

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Abstract

As decarbonization efforts accelerate, renewable energy is expected to grow substantially. However, increasing curtailment of renewable output has emerged as a major challenge in Japan. From a power system cost perspective, guiding the location of data centers (DCs) and other large electricity-consuming facilities to regions with abundant renewable energy potential and sufficient supply capacity can be an effective strategy. In particular, for data centers dedicated to generative AI model training, locational optimization offers a promising approach to align growing electricity demand with renewable resource availability. Flexible operation of such facilities can further contribute to system stability by reducing renewable energy curtailment and improving the operational efficiency of thermal power plants. For AI data centers, this flexibility may involve adjusting training schedules in response to fluctuations in renewable output or system conditions. Our results suggest that optimal siting can enhance renewable energy utilization and reduce overall system costs. In addition, demand-side flexibility can limit the need for new investments in thermal generation plants and promote the deployment of battery storage. Therefore, both siting and operational flexibility of emerging power demands should be quantitatively assessed and integrated into future policy design and technological development to support a more sustainable power system.

***Keywords**:* Demand response, Data Center, Thermal power plant, Curtailment

1. Introduction

In February 2025, the Japanese government approved the Seventh Strategic Energy Plan[1)], accompanied by outlooks toward 2040. One notable difference from the Sixth Strategic Energy Plan is the expectation that the introduction of electricity-consuming facilities and equipment, such as data centers (DCs), will increase substantially in the future. As a result, the Seventh Strategic Energy Plan points out the possibility that electricity demand, which had been on a declining trend, may turn upward over the long term. In the near term, in addition to the expansion of data processing volumes, the use of new services such as generative artificial intelligence (AI) is expected to grow.

Conventionally, data center expansion in Japan has been concentrated in urban areas due to concerns regarding latency and accessibility. With the increase of such new electricity-consuming facilities, concerns have been raised regarding constraints in power grids and electricity supply capacity. The Ministry of Economy, Trade and Industry (METI) has identified these issues as challenges for power networks in the “Study Group on Localized Increases in Electricity Demand and Transmission and Distribution Networks”[2)].

As one potential means of alleviating these constraints, dispersing the locations of electricity-consuming facilities is expected to mitigate renewable energy curtailment—an issue currently faced—and to reduce the burden on power grids. METI and the Ministry of Internal Affairs and Communications have established the “Public–Private Council on Watt–Bit Collaboration”[3)] as a forum for coordination and cooperation among public and private stakeholders, and are examining responses to new electricity demand through coordinated industrial location planning. In analyses related to Watt–Bit collaboration, Mitsubishi Research Institute (2025a)[4)] and Mitsubishi Research Institute (2025b)[5)]) evaluated the benefits of geographically dispersing DC locations.

In addition to locational considerations, the potential of demand response—controlling electricity consumption by varying data processing volumes in DC operations—has been identified as a measure to ease grid constraints (EPRI (2024)[6)]). The International Energy Agency (2025)[7)] has indicated that in major economies such as the United States, Europe, and China, even if DCs can flexibly adjust operations for only about 0.1–1% of the time, the current power system would have sufficient capacity to integrate all new DC capacity introduced by 2035.

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Regarding control of data processing volumes, demonstration projects have been reported in Japan by Tokyo Electric Power Company Power Grid and Hitachi[8], focusing on workload shifting among DCs. As an overseas analytical example, Zheng et al.[9] analyzed the effects of migrating DC loads from the PJM region to the CAISO region in the United States, showing that such migration could absorb up to 62% of surplus variable renewable energy generation in 2019 and contribute to an annual CO_2 reduction of 239 thousand tons.

Based on these prior studies and trends in technological feasibility, this analysis uses the IEEJ power generation mix model to examine the impacts of the location of DCs and other demand on the power system. For Japan-specific modeling studies, Naoi et al.[10] analyzed optimal DC siting and spatiotemporal load distribution, showing that the effectiveness of supply–demand balancing increases in the order of locational optimization, spatial load distribution, and temporal distribution.

Similarly, Taniguchi et al. [11] demonstrated that combining active load control of DCs with locational optimization can maximize the utilization of variable renewable energy (VRE) and suppress transmission expansion. While these studies indicate that DC siting and active load control contribute to narrowing supply–demand gaps and improving the efficiency of VRE and transmission investments, they do not analyze the impacts on investment in dispatchable power sources such as thermal generation, nor do they assess the effects on system operation or total power system costs.

Accordingly, this study follows the methodologies of prior research and focuses on analyzing the extent to which the location and active operational control and flexibility of electricity-consuming facilities, such as DCs affect dispatchable generation investment and system costs.

2. Methodology

2.1 Analytical approach

This analysis employs a power generation mix model jointly developed by the Institute of Energy Economics, Japan, and the University of Tokyo[12] (excluding constraints related to load frequency control reserves). The model covers Japan, excluding Okinawa, and analyzes the impacts of electricity-consuming facilities—primarily DCs—on future generation mixes. The model incorporates electricity demand and existing nuclear capacity as exogenous parameters to determine annual operational patterns of generation, as well as deployment levels of VRE and decarbonized thermal generation. In addition, the location and operational patterns of electricity-consuming facilities represented by DCs are also included as optimization variables. This enables evaluation of the effects of guiding DC deployment to regions with high wind and solar potential and of introducing operational flexibility in DC demand. The objective function minimizes total power system costs in 2050, expressed as: Eq. (1)

$$TC = \sum_i (G_i \cdot PF_i \cdot k_i + \sum_{d,t} PV_i \cdot x_{i,d,t}) + \sum_j cs_j + \sum_k dc_k \qquad (1)$$

where TC denotes total system cost; G_i denotes the annual cost rate of generation type i; PF_i denotes the construction cost; k_i denotes installed capacity; PV_i denotes fuel cost; $x_{i,d,t}$ denotes output at day d, hour t; cs_j denotes storage cost; and dc_k denotes the cost of electricity-consuming facilities.

The supply–demand balance constraint is defined for each node and hour, with conventional demand and DC demand explicitly separated on the right-hand side.

$$\sum_{i\in I_n} x_{i,d,t} + \sum_{j\in J_n} \left(dis_{j,d,t} - cha_{j,d,t}\right) + \sum_{b=1} CC_{n,b} \times \left(tp_{b,d,t} - tn_{b,d,t}\right) - loss_{b,d,t} = LOAD_{n,d,t} + dcd_{n,d,t} \qquad (2)$$

where $x_{i,d,t}$ denotes output at day d, hour t; $dis_{j,d,t}$ denotes the discharging power of electricity storage system j at day d and hour t; $cha_{j,d,t}$ denotes the charging power of electricity storage system j at day d and hour t; $CC_{n,b}$ denotes the node–branch incidence matrix representing the connection between node n and branch b; $tp_{b,d,t}$ denotes the power flow on branch b in the forward direction at day d and hour t; $tn_{b,d,t}$ denotes the power flow on branch b in the reverse direction at day d and hour t; $loss_{n,b,t}$ denotes the transmission loss on branch b at day d and hour t; $LOAD_{n,d,t}$ denotes the electric power demand at node n at day d and hour t, excluding DC loads and similar components; $dcd_{n,d,t}$ denotes the electric power demand from DC loads and related components at node n at day d and hour t.

DC demand is modeled such that hourly variations at each node are allowed, while the sum of these demands equals the annual total electricity consumption by DCs, thereby representing flexible facility operation.

$$\sum_n \sum_d \sum_t dcd_{n,d,t} = TDCD \qquad (3)$$

where $TDCD$ denotes the annual total electricity consumption

2.2 Assumptions

The analysis assumes achievement of carbon neutrality in the power sector by 2050. Annual electricity demand is set at approximately 1,500 TWh, based on IEEJ analyses presented to the Basic Policy Subcommittee in collaboration with Yokohama National University and Ritsumeikan Asia Pacific University[13]. Of this total, DC demand is assumed to be 200 TWh annually. Technologies subject to cost optimization include new ammonia-fired thermal power, VRE (i.e. solar photovoltaic (PV) and wind), and battery storage. Nuclear power capacity is fixed at 36.9 GW with a capacity factor of 71.8%, and other renewable sources are treated as exogenous based on the Seventh Strategic Energy Plan. Transmission expansion is defined by the national grid master plan of OCCTO[14] as exogenous. Existing thermal plants remaining in 2050 are assumed to be equipped with carbon capture and storage (CCS), capturing 90% of CO_2 emissions. Upper bounds on VRE deployment are set based on prior assessments (Obane, et al.[15]).

2.3 Case settings

To quantitatively evaluate the impacts of increased DC demand, four cases are defined (**Table 1**). In Japan, newly developed electricity-consuming facilities—particularly DCs—tend to be sited in locations that satisfy multiple conditions: good accessibility from major demand centers for processing services such as the Tokyo metropolitan area and the Keihanshin region; availability of large parcels of land required for construction; secure access to industrial water; favorable conditions for grid interconnection; and low exposure to natural disaster risks, including tsunamis. Recently, new DC developments have increased markedly within the service areas of Tokyo Electric Power Company (e.g. Inzai City, central Tokyo, and Tsukuba City), Kansai Electric Power Company (e.g. Osaka and the Keihanna region), and Hokkaido Electric Power Company (e.g. Ishikari City)[16].

Based on these observed trends, this study defines a fixed-location case (Case 1: Reference), in which DCs and similar facilities continue to be located primarily in urban and metropolitan areas. In this case, the regional allocation of electricity demand from DCs and related facilities is determined on the basis of the locations of existing DCs as well as sites where new DC developments have been planned[16]. In contrast, the location-optimization case (Case 2) imposes none of the above siting constraints; instead, facility locations are endogenously determined through cost minimization within the model. Specifically, under the location-optimization case, the model determines how an annual electricity demand of 200 TWh attributable to DCs and similar facilities is distributed across regions.

It is often argued that, due to the characteristics of DC operations, certain applications require proximity to urban areas in order to mitigate concerns over information processing latency. Naoi et al.[10] provide a detailed analysis of this issue. However, in this study, the impacts of location-induced latency are not explicitly considered. With respect to operational assumptions, Case 1 assumes that electricity demand from DCs and related facilities remains nearly constant over time. By contrast, Case 3 allows hourly demand to vary by up to ±1% per hour. In addition, demand can be reduced to as low as 50% of the maximum demand of DCs and related facilities at each location.

Table 1: Case settings

	Fixed-location	Location-optimization
Fixed-demand	Case 1: Reference	Case 2: Location-optimization
Flexible-operation	Case 3: Flexible operation	Case 4: Location-optimization and flexible operation

3. Results and Discussion

3.1 Reference case

In the reference case, the model deploys 248 GW of solar PV and 109 GW of wind power (**Fig. 1**). Excluding storage and pumped hydro, renewable energy accounts for 53% of total generation, close to the 2040 power mix presented in the Seventh Strategic Energy Plan[1] (**Fig. 2**). To accommodate increased demand including DCs, renewable deployment expands and existing thermal plants are retrofitted with CCS. Where supply capacity remains insufficient as plants reach the end of their operational lifetimes, new ammonia-fired power plants are introduced. Battery storage reaches 81 GW, contributing to supply–demand balancing (**Fig. 1**).

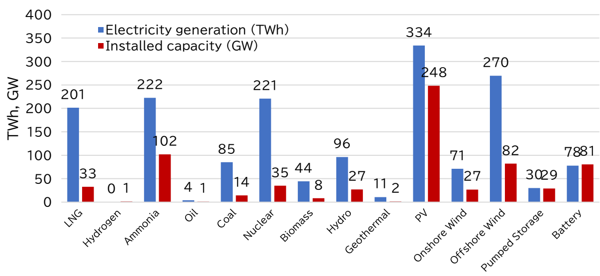

Fig. 1 Electricity generation and installed capacity by technology (Case 1)

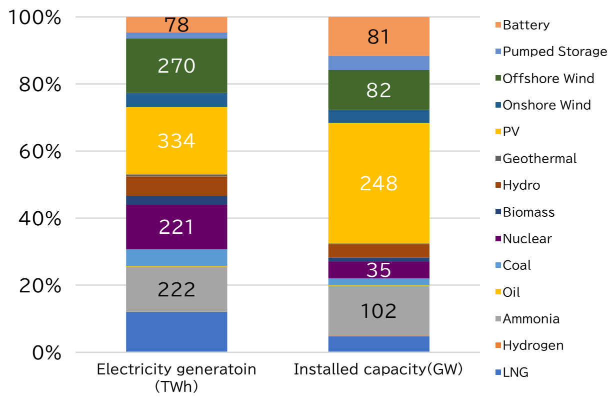

Fig. 2 Shares of electricity generation and installed capacity by technology (Case 1)

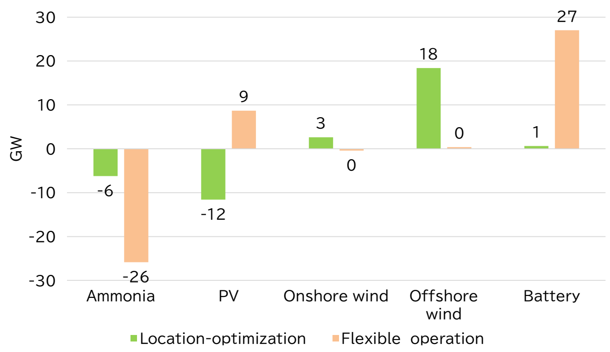

Fig. 4 Changes in installed capacity relative to the reference case

3.2 Location-optimization and flexible operation cases

Compared with the reference case (Case 1), the location-optimization case (Case 2) results in DCs being sited in rural areas rather than urban centers from a system cost minimization perspective (**Fig. 3**).

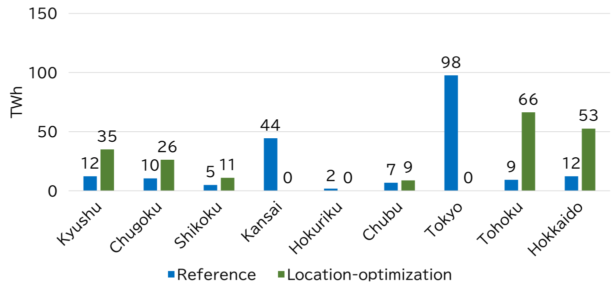

Fig. 3 Distribution of electricity demand from data centers and related facilities by utility service area (Reference and location-optimization cases)

With respect to generation capacity, in the reference case (Case 1), increasing electricity demand leads to a substantial expansion of newly installed ammonia-fired power plants, particularly within the service areas of Tokyo Electric Power Company and Kansai Electric Power Company. In the location-optimization case (Case 2), installed capacity of ammonia-fired power plants and PV generation decreases relative to the reference case, while onshore and offshore wind power capacity increases significantly in non-urban regions. Consequently, new ammonia-fired generation and PV capacity decrease, while onshore and offshore wind capacity increases in non-urban regions (**Fig. 4**). In the flexible operation case (Case 3), ammonia-fired capacity declines substantially, while PV and battery storage increase. This suggests that flexible DC demand reduces reliance on thermal generation for balancing, making combinations of PV and storage more cost-effective (**Fig. 4**).

Urban areas account for a large share of total generation in line with the growth in electricity demand from data centers and related facilities (**Fig. 5**). In contrast, in Case 2, installed capacity of offshore wind power increases markedly, particularly in regions outside major urban areas, as shown in **Fig. 4**. As a result, electricity generation shifts from urban areas to non-urban regions relative to Case 1 (**Fig. 6**). In Case 3, although installed generation capacity decreases for ammonia-fired power plants and increases for battery storage compared with Case 1, there is no substantial difference in electricity generation on an energy basis relative to Case 1 (**Fig. 7**).

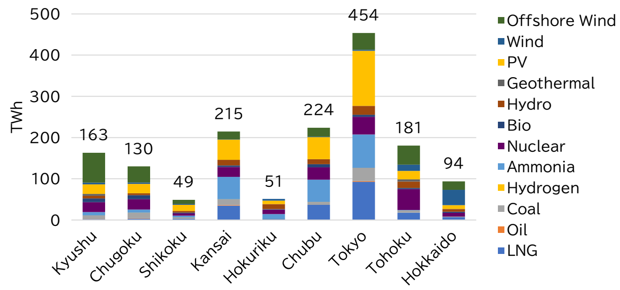

Fig.5 Regional electricity generation (Case 1)

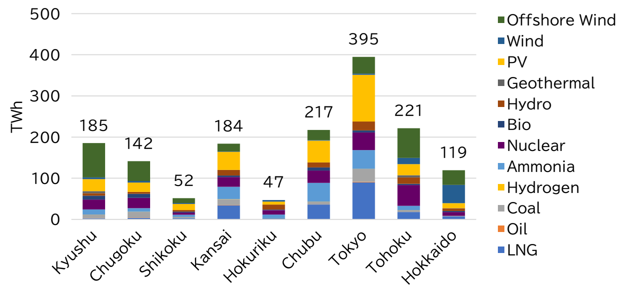

Fig.6 Regional electricity generation (Case 2)

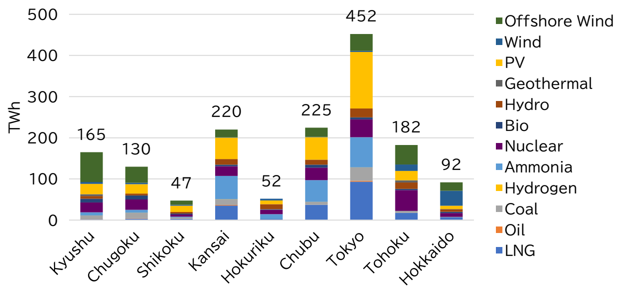

Fig.7 Regional electricity generation (Case 3)

In terms of generation output, locational optimization shifts generation from urban to regional areas due to increased offshore wind deployment. Demand flexibility mainly affects capacity composition rather than total generation output. Cost analysis shows that the optimization of facility siting yields substantial reductions in fuel costs, primarily by facilitating the integration of higher shares of VRE, while demand flexibility reduces capital investment in thermal generation despite increased storage investment. When both measures are implemented simultaneously, annual system costs decline by the order of JPY 1 trillion (**Fig. 8**).

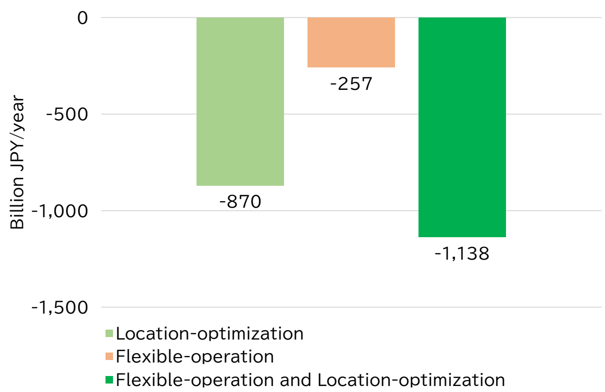

Fig. 8 Changes in annual costs (2022 real prices) relative to the reference case

3.3 Discussion

Based on the analytical results, consistent with previous studies, optimizing the location of DCs and related facilities contributes to the expansion of VRE deployment in Japan and to the mitigation of regional supply–demand imbalances in the power system. In addition, demand-side flexibility has the potential to substitute for the reliability from thermal power plants and balancing services traditionally provided by thermal power plants, while enabling greater utilization of VRE.

From an economic perspective, it is therefore worth considering more flexible siting strategies for DCs that are not limited to urban areas but instead reflect application-specific requirements, even when potential concerns regarding information processing latency are taken into account. Moreover, flexible operation of DCs and related facilities can contribute to power system stability and cost reductions by reducing renewable energy curtailment, enabling more efficient operation of thermal power plants, and lowering overall capacity requirements. Taking DCs for generative AI applications as an example, ongoing discussions on technical feasibility suggest that effective implementation of flexible operation—by scheduling AI model training in consideration of power supply–demand conditions—can contribute to both power system stabilization and cost reductions.

To realize and scale up these benefits, it is therefore essential to advance institutional and regulatory measures that promote the optimization of DC locations and their flexible operation. From the perspective that DCs and related facilities can play an important role in the power system under concepts such as the integration of electricity and digital infrastructure (“watt–bit integration”), policies that actively support their strategic deployment and operation will be increasingly important.

4. Conclusion

This study examined the potential contributions of the siting and operational flexibility of emerging electricity demand from DCs and related facilities—expected to increase in Japan—by applying a power generation mix model. The analysis focused on how both location optimization and flexible operation of such facilities could contribute to the performance of the power system.

The results indicate that optimizing the location of DCs and related facilities can lead to cost reductions by promoting greater utilization of renewable energy. In addition, demand flexibility is shown to have the potential to suppress new investments in thermal power plants as balancing resources and to encourage a shift toward battery storage instead. As a direction for future research, this analysis treated DCs and related facilities as a single category of electricity demand.

However, as suggested by previous studies, a more precise assessment of locational and operational flexibility would require disaggregated analysis by application type, given the heterogeneity in siting constraints and operational requirements across different uses.

Moreover, while this study evaluated the potential for cost reductions at the level of the overall power system, the allocation of these benefits—namely, who captures the economic gains and through what mechanisms—will be an important consideration in the context of institutional and market design.

With regard to the utilization of emerging electricity demand from DCs and related facilities, further technical assessment is needed, along with a quantitative evaluation of both the benefits and drawbacks. Based on such evidence, it will be essential to advance institutional design and technological development in an integrated manner, informed by further technical validation and quantitative assessment.

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