Integrated Spatial Strategies for Electricity Demand and Supply

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Abstract

Rising electricity demand calls for new adaptation strategies. Beyond expanding supply capacity, integrated siting of demand and generation emerges as an overlooked solution. Some case studies have demonstrated renewable-energy-driven demand relocation can be mutually beneficial for end users and power systems.

Introduction

The pursuit of further socioeconomic growth drives substantial increases in electricity demand. According to scenarios in IPCC AR6, global electricity demand may rise from approximately 25 PWh today to more than 80 PWh by 2100, and up to roughly 170 PWh under stringent climate-mitigation and adaptation pathways (Fig. 1) [1]. In the short term, additional demand raises CO_2 emissions as fossil-fired plants are ramped up; in the long term, it increases pressure on clean-energy investment, threatening the feasibility of ambitious climate goals such as the 1.5 °C target. Rising demand also implies higher prices, exacerbating energy poverty and energy-access challenges. Yet strategies to address these risks from surging demand remain underexplored. By reconsidering where new demand emerges, power systems may unlock overlooked, transformative solutions.

Rising Demand and Adaptation Strategies

While the trajectory of future economic activity remains uncertain, electricity demand is very likely to increase substantially. Low energy demand pathways that ensure human well-being while mitigating planetary pressures have been widely explored. Yet even as these pathways reduce overall final energy use, they substantially increase final electricity consumption. For instance, in the LED scenario developed by Grubler et al. [2], total final energy demand falls by about 40%, but electricity demand increases by a factor of 1.8 in 2050.

If demand continues to grow, can the challenge be solved simply by adding generation and transmission? Historically, yes: utilities expanded supply and networks. Hundreds of megawatt-class fossil-fuel plants and gigawatt-class nuclear units were built to meet growth. Once power infrastructure matured, new MW-scale loads were often welcomed because they raised utilization of existing assets. However, new GW-scale consumers—such as semiconductor fabs or data centers—now risk straining the residual capacity of existing infrastructure, necessitating additional investment. In most countries under climate targets, new fossil plants

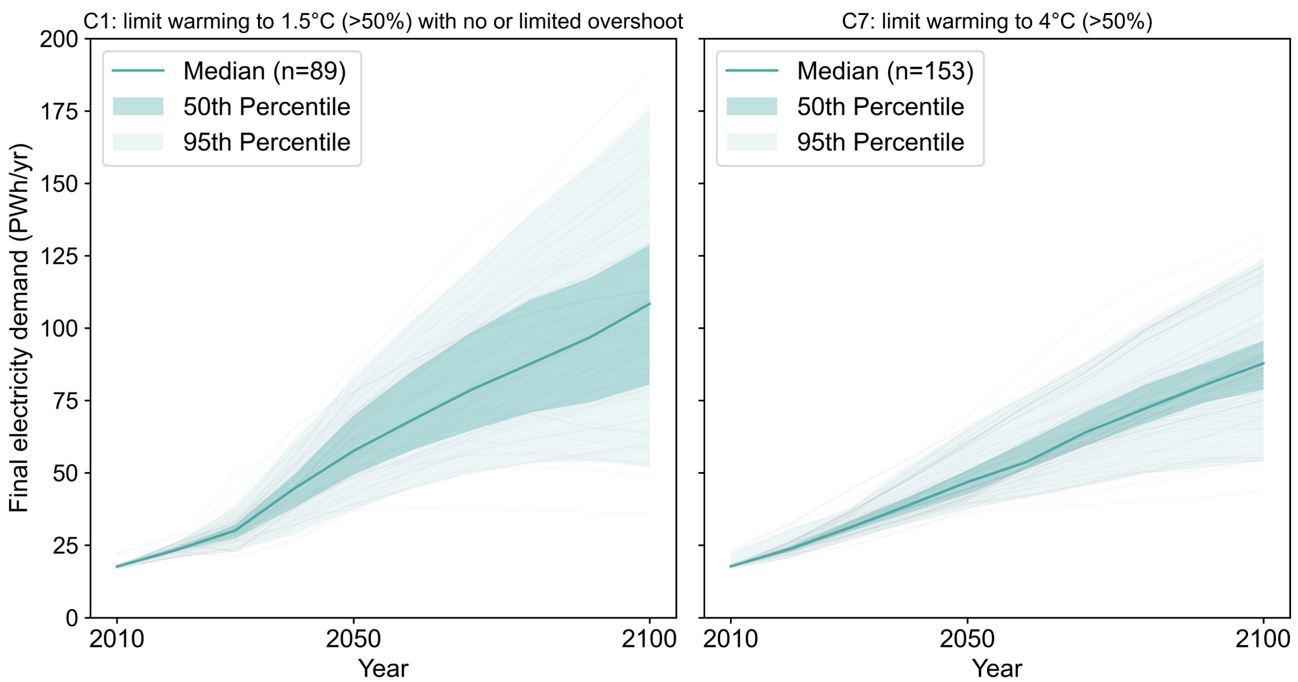

Figure 1: Global final electricity demand trajectories under the 1.5 °C target (left) and 4 °C pathways (right). n *represents the number of scenarios. Source: IPCC AR6 scenarios database* [1].

are politically, financially, and socially difficult to implement, while nuclear power continues to face unresolved issues of social acceptance, waste management, and proliferation concerns. In short, society can no longer rely on large, centralized supply-side expansions, even as GW-scale demand additions are emerging.

Reactivating dormant nuclear plants offers a partial, location-specific solution. Microsoft, for example, has announced plans to colocate a data center with a reactivated Three Mile Island nuclear facility. Such opportunities are not universally replicable, but they demonstrate how power-hungry end users are. Renewable energy remains the other major clean option. Although its expansion has provoked conflicts with biodiversity, landscapes, and other local values, significant potential remains. Yet cost-competitive, GW-scale renewable resources are often far from demand centers. This raises a fundamental choice: should we transmit renewable electricity over long distances to consumers, or should new consumers relocate near renewable supply? Conventional power-system planning has overwhelmingly prioritized the first option. Emerging studies, however, suggest that the second—demand relocation—can be mutually beneficial for consumers and the power system [3,4]. A few case studies of electricity-intensive industries (e.g., chemicals, data centers) indicate that renewables can attract new demand; this mechanism is often termed the "renewables pull effect" or "green relocation."

Potential of Strategic Siting: A Case Study of Data Centers in Japan

Japan provides a timely case to explore these dynamics. Electricity-intensive new demands—including data centers, semiconductor plants, electric arc furnaces, and hydrogen electrolysis—are expected to grow rapidly. In February 2025, citing these emerging loads, the Japanese government shifted its stance on nuclear power: after years of aiming for reductions, it announced a policy to promote nuclear restarts. Simultaneously, it introduced the Green Transformation (GX) growth strategy, emphasizing spatial integration of supply and demand ("GX industrial siting") to better utilize distributed clean-power sources. This policy shift reflects a structural imbalance. As in many countries, Japanese data centers are highly concentrated in metropolitan hubs, particularly Tokyo and Osaka—a siting pattern that historically minimized communication latency by clustering data centers, internet exchanges, and landing stations near end users. Is such spatial concentration still sustainable in a decarbonized future? What siting strategies should guide future industries and power systems?

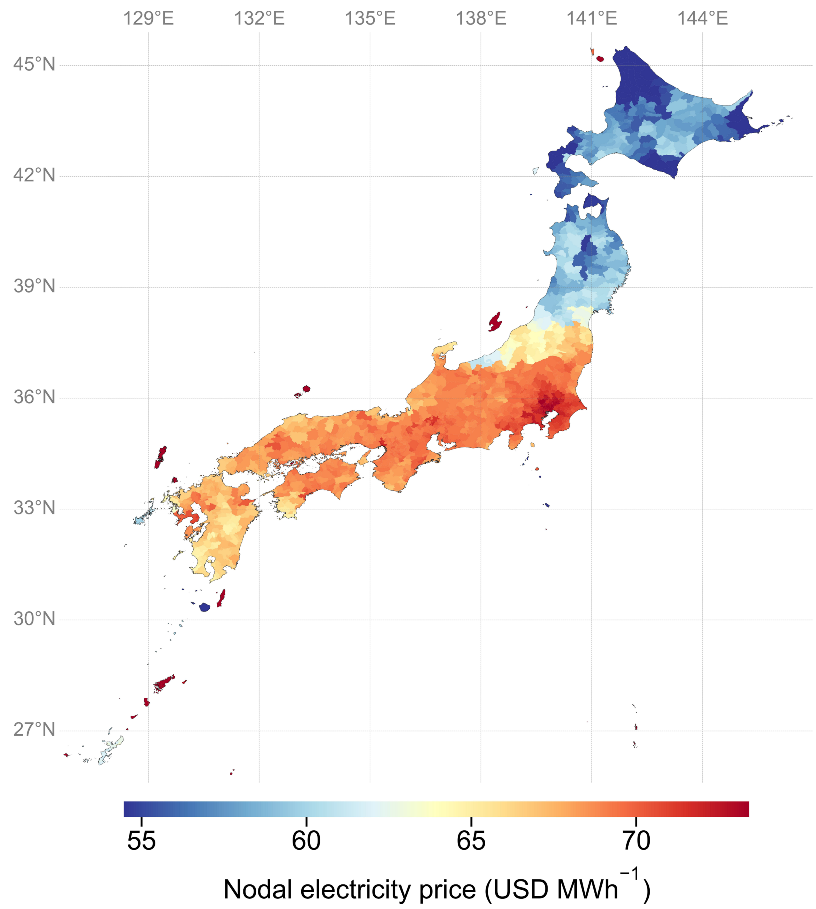

Figure 2: Nodal electricity prices for Japan in 2050 under the 1.5 °C target.

To address these questions, I conducted a case study of data-center siting in Japan. A high-resolution power system model covering all 1,741 municipalities was used to examine various siting strategies of data centers under the commitment to the 1.5 °C target. As a result, if data centers continue to increase (by about 8% of national electricity demand in 2050) and concentrate in metropolitan areas, system costs rise by 5.1% compared to the case without data center expansion. In contrast, if data centers pursue locations aligned with inexpensive and clean electricity, the additional system costs can be reduced by up to 19%. The optimal siting patterns are well explained by nodal electricity prices (i.e., average local marginal prices (LMP)). Under a 1.5 °C scenario for 2050, these nodal prices vary widely: they are highest on isolated islands and in the congested Tokyo metropolitan area, and lowest in Hokkaido, where offshore wind resources are abundant (Fig. 2). Such spatial variation of LMP is also observed in the United States [5]. In optimized siting scenarios, these low-cost nodes emerge as prime candidates for new data centers. For example, if retail electricity prices reflect nodal prices, relocating a data center from the Tokyo metropolitan area (e.g., Inzai City) to Hokkaido (e.g., Ishikari City) could reduce per-kWh electricity costs by ~19.5%, even if region-specific climate conditions increase electricity demand by 3%. This implies that strategic siting can reduce both end-user electricity expenditure and the investment required for power-system decarbonization.

Conclusions

Strategic demand relocation is an overlooked but beneficial option for adapting to rising electricity demand. Spatially aligning large-scale demand with clean power sources can generate win–win outcomes for both system operators and consumers.

While case studies demonstrate this potential, practical barriers remain. For data centers specifically, the emergence of ultra-low-latency technologies such as electro-optics is promising, yet further validation is needed to ensure that both communication quality and power system security can be secured under dispersed siting. For other electricity-intensive industries, such as electric arc furnaces or semiconductor fabrication, similar system-cost benefits may be achievable. However, these potential gains must be weighed against possible increases in supply-chain costs for materials and products, which could offset savings from reduced energy expenditure. Ultimately, these findings motivate further research on the coupling between the electricity system and other societal infrastructures—such as communication networks and industrial supply chains. Addressing these interdependencies will be essential to reconcile growth, decarbonization, and resilience in the decades ahead.

Reference

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