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# Spatially explicit data center layouts integrated with green power direct connection

**Mengyao Han**[1,3,4,*] **and Zidi Sun**[1,2,3]

[1]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[2]School of Geography and Information Engineering, China University of Geosciences, Wuhan 430074, China

[3]College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

[4]Centre for Environment, Energy and Natural Resource Governance, University of Cambridge, Cambridge CB2 3QZ, UK

*Correspondence: hanmy@igsnrr.ac.cn

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**Dear Editor,**

The global proliferation of digital infrastructure has precipitated an unprecedented surge in data center energy consumption, which now accounts for approximately 1-1.5% of worldwide electricity use and continues to escalate with the rapid deployment of artificial intelligence workloads.[1] Early research established energy consumption models for data centers, highlighting the critical need for systematic approaches to quantify and mitigate their environmental footprint.[2] Previous studies revealed that while efficiency improvements have historically tempered energy growth, the exponential rise in computational demand, particularly from AI training and inference, threatens to reverse these gains through rebound effects.[3] In response, the research community has increasingly turned to carbon-aware computing paradigms, in which workloads are dynamically shifted across geographically distributed data centers to exploit temporal and spatial variations in grid carbon intensity.[4,5]

Empirical investigations have shown that inter-data center load migration can substantially reduce renewable curtailment while lowering carbon emissions, laying the groundwork for geographically distributed green computing architectures.[5] Concurrently, comprehensive environmental footprint assessments of national data center fleets have underscored the urgency of transitioning from fossil-dependent centralized models to renewable-integrated

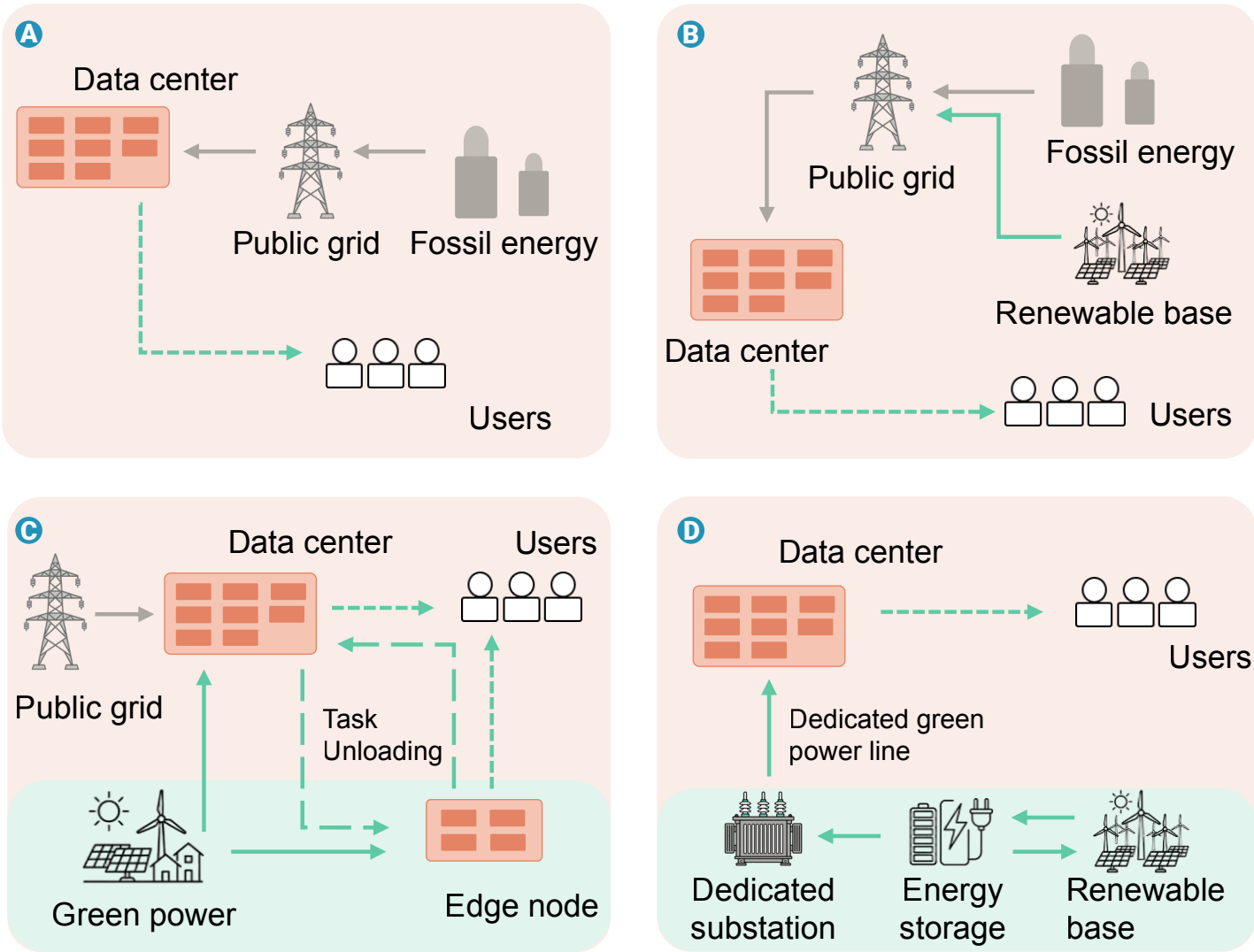



Figure 1. Spatial layouts of integrated computing and power systems.

distributed systems.[6] The integration of edge computing with renewable energy sources has further emerged as a pivotal strategy, enabling low-latency inference at the network periphery while offloading energy-intensive training tasks to green compute centers located in regions with abundant renewable resources.[7]

## NOTE: DRAWN BY THE AUTHORS

Figure 1 illustrates four spatial layouts of integrated computing and power systems transitioning from traditional fossil fuel reliance to renewable-powered computing models. In the conventional grid supply model (Figure 1A), fossil energy is delivered through the public grid to a data center that provides computing services to users. The hybrid power supply model (Figure 1B) represents a transitional phase in which both fossil energy and renewable energy are integrated into the public grid and jointly supply the data center, thereby reducing but not eliminating its reliance on conventional energy. The distributed collaboration model (Figure 1C) combines a central data center with edge nodes located close to users. The public grid supplies the central data center, while locally available green power supports both the data center and edge nodes. Edge nodes can perform low-latency inference, while the central data center handles training and batch-processing tasks, offloading work between the center and edge as appropriate. The centralized renewable supply model (Figure 1D) connects a large-scale renewable energy base and energy storage system to a data center through a dedicated substation and green power line. This configuration concentrates renewable generation, storage and electricity delivery within a coordinated supply system, enabling large scale green power to be delivered directly to a centralized data center. Together, these layouts offer distinct pathways to reduce the carbon intensity of computing infrastructure. The transition involves changes not only in energy sources but also in power-supply arrangements, workload placement, and system architecture from conventional grid dependence, through hybrid fossil renewable supply and distributed computing collaboration to centralized renewable supply through dedicated power infrastructure.

This analytical framework yields several policy implications. First, regulatory instruments such as carbon-intensity disclosure mandates and green procurement standards can accelerate the transition from fossil grid dependence to hybrid renewable integration by incentivizing power purchase agreements and renewable energy certificates, while grid planning frameworks should be modernized to accommodate the simultaneous integration of conventional and renewable energy sources. Second, the distributed collaboration model necessitates policy support for edge infrastructure deployment and coordination between central data centers and edge nodes, including carbon-aware task-allocation protocols, transactive energy market mechanisms, and harmonized carbon accounting standards. Third, realizing the centralized renewable supply model requires coordinated land-use planning and grid-interconnection policies that support large-scale renewable energy bases, energy storage facilities, dedicated substations, and green power lines, complemented by permitting procedures and investment incentives or tradable carbon credits for the direct delivery of renewable electricity. Fourth, green financing mechanisms and sustainable infrastructure bonds should be scaled up to de-risk capital-intensive investments in renewable generation, energy storage, dedicated power infrastructure, and low-carbon computing facilities. These above implication levers should be sequenced to align technological evolution with carbon reduction targets, ensuring that computing capacity expansion does not come at the expense of climate commitments.

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## AUTHOR CONTRIBUTIONS

M.H. designed the research; M.H. and Z.S. performed the investigation and validation; M.H. and Z.S. prepared the original draft and conducted data curation; M.H. reviewed and edited the manuscript. All authors contributed to discussions on the framework and to the editing of the article.

## DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.