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FROM ENERGY-HUNGRY TO ENERGY-SMART. DESIGNING SUSTAINABLE AND RESILIENT DATA CENTERS AS NEW INFRASTRUCTURES OF THE DIGITAL AGE / Liboni, M.. - ELETTRONICO. - (2026), pp. 1-13. (Cumulus Athens 2026: Roots/Routes in Design Athens (GRC) 5–9 May 2026).

Availability:

This version is available at: 11583/3016791 since: 2026-10-19T16:11:23Z

Publisher:

Cumulus Association

Published

DOI:

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FROM ENERGY-HUNGRY TO ENERGY-SMART. DESIGNING SUSTAINABLE AND RESILIENT DATA CENTERS AS NEW INFRASTRUCTURES OF THE DIGITAL AGE

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ABSTRACT

In an era increasingly defined by digital infrastructures, data centers have become the invisible backbone of contemporary life—supporting communication, creativity, and global economies. Yet their environmental impact is staggering: energy consumption, water use, and carbon emissions are rising in parallel with our digital dependence. This paper investigates how design thinking and sustainable design practices can reimagine data centers as resilient ecosystems rather than resource-hungry machines. The study begins by tracing the roots of data center design—rooted in the industrial logic of efficiency, centralization, and control. Historically, data centers have been conceived as neutral, purely technical spaces. However, as their ecological footprint becomes increasingly visible, there is an urgent need to redefine their design logic, integrating environmental and social dimensions. As Fry (2009) argues, design must move from sustaining existing systems to regenerating futures, and this transition is crucial when addressing the material and energetic infrastructures of the digital age.

Through the lens of design research (Manzini, 2015; Fry, 2009), the paper proposes a methodological shift toward “energy-smart design”, a framework that combines spatial design, materials innovation, and lifecycle carbon accounting. By integrating tools such as CO₂ footprinting, circular material flows, and AI-driven energy optimization, data centers can evolve into living laboratories of sustainability. Case studies from Europe and the Mediterranean region illustrate how architectural, environmental, and digital design can converge to create adaptive infrastructures—structures capable of responding dynamically to local climate conditions and energy availability.

Within the routes of innovation, the paper discusses how cross-disciplinary design practices—bridging architecture, interaction design, and systems thinking—can lead to new paradigms of infrastructural resilience. Rather than merely hosting data, next-generation data centers can act as distributed energy nodes, reusing waste heat, harvesting renewable energy, and embedding sustainable aesthetics into technological landscapes. Ultimately, the paper argues that the future of design lies in reimagining the

digital infrastructures that sustain our daily lives. By designing data centers not as abstract machines but as ecological and cultural artifacts, we can reconnect technological progress with planetary responsibility—transforming the “roots” of the digital era into new “routes” toward sustainability, regeneration, and resilience.

Key Words: Data Center, Energy Consumption, CO2 Emission, Systemic Design

1 INTRODUCTION

In the era of digital infrastructures, data centers constitute the invisible backbone of contemporary life. They sustain communication, creativity, economic systems, and global knowledge flows, positioning themselves as critical infrastructures of the digital age. The widespread diffusion of large-scale artificial intelligence models, including Large Language Models (LLMs), has accelerated the demand for energy-intensive computational infrastructures, making data centers a critical node in the digital transition (Korinek, 2024; Yan et al., 2023). LLMs enable unprecedented levels of cognitive augmentation and productivity (Baryshnikov, 2024), yet their operation depends on resource-intensive computational ecosystems. This condition generates a structural paradox. While data centers enable digital transformation, their operation entails high energy consumption, significant water use for cooling, carbon emissions, and the generation of electronic waste. The infrastructure that sustains artificial intelligence and the data economy thus reveals its materiality and ecological cost, often obscured within dominant narratives of digital innovation (Galaz et al., 2021). This scenario raises a crucial question for design research: how can data centers be reimagined not as energy-intensive machines conceived under an industrial logic of efficiency and control, but as resilient ecosystems capable of integrating environmental, territorial, and social dimensions? Traditional approaches tend to focus on algorithmic efficiency or model performance optimization (Dhiman et al., 2024), frequently neglecting the infrastructural scale. Design research, by contrast, provides tools to interpret data centers as designable socio-technical systems, in which spatial, material, and energy choices directly affect ecological balances (Callicott, 2013).

As Fry (2009) argues, design cannot merely sustain existing systems but must contribute to the generation of regenerative futures. In parallel, Parikka (2015) emphasizes that the digital is inseparable from its geological and energetic substrates: there is no immaterial infrastructure. Within this theoretical framework, the present contribution proposes an energy-smart design framework, understood as a design approach integrating life-cycle carbon accounting, material innovation, and renewable energy integration (Raihan, 2024). The objective is to investigate how data centers may evolve from centralized, energy-intensive infrastructures into adaptive and resilient nodes capable of engaging with local territories, reusing waste heat, dynamically optimizing energy flows, and incorporating circular economy principles. In doing so, the material “roots” of the digital era may be transformed into new design “routes” toward systemic sustainability and resilience.

2 HISTORICAL EVOLUTION AND LIMITS OF TRADITIONAL DATA CENTERS

Historically, data centers have been designed according to an industrial logic grounded in efficiency, centralization, and control. Conceived as neutral and purely technical infrastructures, these architectures have prioritized computational density, security, and operational continuity, relegating environmental and territorial dimensions to a secondary role. This paradigm, consistent with industrial modernity, now reveals its limitations in the face of the climate crisis and growing global energy demand. The sustainability paradox of data centers lies at the intersection of multiple research domains: digital infrastructure design and management, energy systems, and circular economy (Arquilla & Paracoli, 2023). Data centers are not merely technological containers, but complex socio-technical infrastructures mediating between data flows, material resources, and global energy systems. With the rise of artificial intelligence, the training and inference of computational models require high-density clusters of GPUs, TPUs, and specialized hardware concentrated in hyperscale data centers. This increase in computational power translates into growing electricity demand, often still partially dependent on fossil fuels, resulting in significant greenhouse gas emissions (Strubell et al., 2019). Strubell and colleagues estimated that training a single large transformer model can generate emissions comparable to those produced by five cars over their entire lifecycle, making visible the environmental impact of the underlying infrastructure. Beyond operational energy consumption, the material dimension of data centers must also be considered: accelerated hardware production and replacement, electronic waste generation, and the extraction of rare earth elements and critical metals for processors and memory systems. These processes entail ecological degradation, water contamination, and social impacts in mining regions, extending the footprint of data centers far beyond the physical boundaries of the facilities that host them. Although part of AI efficiency research focuses on algorithmic optimization and parameter reduction, such strategies are rarely integrated into systemic lifecycle assessments of the broader infrastructure (Patterson et al., 2021). This results in an analytical gap: environmental impact cannot be understood solely at the model level but must be repositioned at the infrastructural and territorial scale. This discrepancy opens a crucial design space in which data center design can mediate between technological performance, energy resilience, and planetary sustainability, shaping new trajectories of energy-smart design.

2.1 Circular Economy and Digital Systems

Circular economy principles provide an operational foundation for rethinking the lifecycle of data centers from raw material extraction to technological waste disposal (Ellen MacArthur Foundation, 2019). Within this framework, data centers cannot be considered merely computational nodes, but material and energy assemblages embedded in global supply and disposal chains.

As emphasized by Manganelli, Soldati, Martirano, and Ramakrishna (2021), sustainable design concerns not only product-level improvements but the reconfiguration of entire technological systems. Applied to data centers, this perspective implies multi-level

strategies: responsible sourcing of critical materials, extension of hardware lifespan through predictive maintenance and modular upgrades, server reuse, component recovery, and structured recycling programs (McDowall et al., 2017). Modular design and component standardization reduce premature obsolescence and facilitate disassembly, transforming infrastructure into an adaptive ecosystem rather than a rigid, linear organism, in alignment with energy-smart design principles. From an energy perspective, integration with low-emission sources represents a crucial lever. In the United States, Amazon Web Services has signed agreements to procure nuclear energy in Pennsylvania, while Microsoft has invested in the development of small modular reactors to power future autonomous data centers. In France, EDF is exploring low-carbon nuclear solutions for the cloud sector. In parallel, in several European contexts — including Norway and Sweden — data centers widely rely on hydropower (Villari, 2022). These strategies demonstrate how energy management and renewable integration can transform data centers into resilient and adaptive infrastructures capable of engaging with local contexts.

2.2 Design Research Perspectives

Design research provides theoretical and operational tools to reinterpret data centers not as mere technical facilities, but as designable ecosystems characterized by interdependencies among material components, energy flows, and social dynamics (Van Wynsberghe, 2021). Systemic design approaches enable the mapping of relationships between digital infrastructures, environmental impacts, and collective benefits, making visible connections often obscured in purely engineering models. Applied to data centers, these perspectives invite their consideration as territorial and ecological devices, rooted in local ecosystems yet producing planetary effects. Interventions on hardware, software, energy architectures, and operational practices thus become strategic design choices capable of mediating between technological performance and ecological responsibility (Geels, 2005). Design research positions itself as a critical mediator, translating ethical and climatic principles into operational strategies for resilient data centers within an energy-smart design paradigm (Orikpete et al., 2023).

3 METHODOLOGY

This study adopts a sustainability-oriented design research methodology situated within the paradigm of Research through Design (RtD), in which knowledge production occurs through the critical elaboration of scenarios, strategies, and design configurations. From this perspective, design is not conceived as a mere technical application, but as an epistemic device capable of rendering visible the interdependencies between digital infrastructures, energy systems, and territorial contexts. In alignment with the systemic design paradigm, the methodology interprets data centers as socio-technical infrastructures embedded within broader material and ecological networks (Leuthe, 2024). The objective is not primary technical measurement of environmental parameters, but the construction of an interpretative framework capable of connecting quantitative evidence available in the literature with systemic and design implications.

The approach unfolds along three interconnected lines of analysis. The first concerns environmental assessment based on secondary data and existing lifecycle studies of data centers, including energy consumption, carbon emissions, water use, and material flows (Mulder, 2014). This analysis builds upon technical studies and peer-reviewed contributions quantifying the environmental impact of large-scale AI training and inference processes (Pachot & Patissier, 2023). The second line consists of a critical examination of the socio-economic dimensions associated with data centers, considering the balance between value generated by digital services and environmental impacts, in light of ongoing debates on the systemic sustainability of technological infrastructures. The third line involves the development of design scenarios and operational criteria aligned with the energy-smart design paradigm. In this phase, international case studies and documented corporate practices are analyzed as empirical configurations translating principles of energy efficiency and circularity into concrete infrastructural solutions (Rambabu et al., 2025). The four case studies examined in this paper: Hamina, Lefdal Mine, EcoDataCenter, and Project Natick; were selected on the basis of three criteria: geographic and climatic diversity within the European context; documented application of at least two energy-smart design strategies (passive cooling, waste heat recovery, renewable integration, or modular construction); and availability of verifiable technical and environmental data in the public domain. The comparative analysis was conducted by mapping each case against the four design dimensions, climatic integration, energy integration, infrastructural symbiosis, and resilient modularity, in order to identify recurring strategies and context-specific adaptations. Data collection relies primarily on secondary sources, peer-reviewed scientific literature, technical reports, and industrial documentation, integrated through systemic mapping tools aimed at highlighting relationships among energy, material, and territorial flows. AI-assisted analytical tools supported the synthesis and organization of sources while maintaining rigorous bibliographic traceability (Thackara, 2005).

4 ENVIRONMENTAL AND MATERIAL IMPACT

Data centers currently represent a critical component of global digital infrastructure, yet their operation generates increasing environmental impacts in terms of energy consumption, CO₂ emissions, water use, and land occupation (Belkhir & Elmeligi, 2018). According to the most recent reports of the International Energy Agency, global data center energy consumption reached approximately 460 TWh in 2022 — around 1.5–2% of total global electricity demand — and projections estimate that this figure could exceed 1,000 TWh by 2026–2030 in the absence of significant efficiency and decarbonization strategies (International Energy Agency, 2024). This expansion poses significant challenges to local electricity grids. In some regions, the share of electricity allocated to data centers is already substantial: in Ireland, data centers accounted for up to 18% of national electricity demand, while in Singapore the share approached 7% in 2020 (Enlit World, 2024).

Energy consumption does not translate exclusively into computation; a significant portion is devoted to cooling systems and auxiliary infrastructure. Traditional cooling systems, such as evaporative towers, can increase overall energy consumption by 30–40% and require substantial water volumes, intensifying pressure on local water resources, particularly in water-stressed regions (Yale Environment 360, 2023).

Energy consumption in data centers also results in considerable greenhouse gas emissions. Recent estimates indicate that global data centers generate hundreds of millions of tons of CO₂ annually, representing a non-negligible contribution to global emissions (Patterson et al., 2021). Hardware production and replacement — including servers, storage devices, and cooling systems — further contribute to the material footprint of infrastructure, generating electronic waste and requiring extraction of critical resources such as rare earth elements and metals (International Telecommunication Union & United Nations Institute for Training and Research, 2024; Andrade et al., 2022; Mulder, 2014; Kemp et al., 2007; Crawford, 2021). Moreover, the physical location of data centers can directly affect land use and urban planning. Large-scale facilities may occupy extensive surfaces, alter local ecosystems, and influence regional energy networks (Giaccardi & Redström, 2020).

Recent cases illustrate how these dynamics have entered public debate and administrative decision-making. In Prince William County, Virginia, approval of a 2,100-acre data center development plan triggered opposition due to loss of historic landscapes, natural habitats, and rural character, leading to legal appeals and tensions between residents and local authorities (Ngata et al., 2025). Similarly, in Potters Bar, United Kingdom, the construction of a large data center on 85 acres of agricultural land classified as “green belt” sparked community protests concerning environmental impact and insufficient public consultation, despite regulatory changes recognizing such infrastructures as critical to digital development (Järvenpää et al., 2023). In the United States, similar projects in San Marcos, Texas, and Montour County, Pennsylvania, have raised concerns regarding water resources, energy consumption, and increased utility costs, in some cases resulting in the rejection of rezoning applications (Giaccardi & Redström, 2020). In many European and Italian cities, pressure for new data center development compounds broader patterns of land consumption in peri-urban areas, where green or agricultural land is sealed for technological infrastructures, affecting mobility systems, urban drainage, and ecological quality.

These data underscore that data centers must be interpreted as material and territorial infrastructures rather than immaterial technologies. Reducing environmental impact requires integrated design and management approaches combining energy efficiency, responsible water use, renewable integration, waste heat recovery, and hardware lifecycle strategies — all core components of the energy-smart design approach proposed in this study (Ceschin & Gaziulusoy, 2020).

5 SUSTAINABLE DATA CENTERS AS EXPRESSIONS OF ENERGY-SMART DESIGN

The analysis highlights the necessity of reorienting data center design toward criteria of energy efficiency, environmental regeneration, and territorial integration (Saeidnia & Ausloos, 2024). The following cases demonstrate how traditionally centralized and energy-intensive infrastructures can evolve into adaptive ecosystems capable of reconciling high computational performance with environmental sustainability and territorial resilience (Bender et al., 2021; Lot et al., 2024).

5.1 Hamina Data Center, Finland

Google's Hamina data center, built within a former paper mill facility, represents an advanced example of integration between digital infrastructure and local context. The facility utilizes seawater from the Gulf of Finland for cooling, reducing water consumption by up to 50% compared to conventional systems, and operates entirely on locally produced renewable energy (Google, 2023). The site achieves an average Power Usage Effectiveness (PUE) of 1.12, among the lowest globally, demonstrating how targeted design strategies can achieve high energy efficiency. Waste heat is partially reused in local industrial applications, mitigating thermal impact on the surrounding environment. Hamina illustrates how careful site selection and cooling system design can transform a data center into a territorially responsive infrastructure.

5.2 Lefdal Mine Datacenter, Norway

Located within a former olivine mine, the Lefdal Mine Datacenter leverages the natural characteristics of its site to achieve significant energy savings (Data Center Dynamics, 2021). The facility operates entirely on hydropower and uses cold fjord water for passive cooling, reducing energy consumption by approximately 85% compared to conventional data centers. Naturally stable internal temperatures minimize the need for mechanical climate control systems, further reducing emissions. Lefdal demonstrates how territorial design and local resource integration can render a data center both energy-efficient and environmentally embedded.

5.3 EcoDataCenter, Falun, Sweden

Sweden's EcoDataCenter in Falun represents a model of urban and territorial regeneration (Vertiv, 2022). Constructed using low-emission materials and powered by a mix of hydropower, wind, and solar energy, the facility reinjects server-generated heat into the municipal district heating network, achieving a positive energy balance and contributing to urban emission reductions. Modular construction facilitates maintenance, upgrades, and hardware reuse, extending infrastructure lifespan. The EcoDataCenter exemplifies how a data center can function as a regenerative energy actor rather than merely an efficient facility.

5.4 Project Natick, Microsoft

Microsoft's Project Natick explored innovative approaches to adaptive underwater data centers off the coast of Scotland (Microsoft, 2020; Papagiannidis et al., 2024). The infrastructure leveraged passive seawater cooling and operated entirely on renewable energy, reducing dependence on terrestrial grids and minimizing land impact. Experimental results indicated a 15% reduction in hardware failure rates compared to land-based facilities, attributed to stable temperature and humidity conditions. Project Natick suggests how decentralized and environmentally integrated data centers may respond dynamically to climatic and infrastructural challenges.

5.5 Comparative Analysis and Energy-Smart Design Criteria

The comparative analysis of Hamina, Lefdal, EcoDataCenter, and Project Natick reveals that sustainability strategies emerge from the interaction between local climatic conditions, energy availability, and design decisions, reinforcing the importance of integrating infrastructure with territorial context (Saeidnia & Ausloos, 2024). In Nordic contexts, reduced energy consumption is enabled by abundant renewable energy and favorable climatic conditions supporting passive or semi-passive cooling systems. Project Natick further expands this perspective, demonstrating how radically alternative cooling configurations can enhance infrastructural resilience (Papagiannidis et al., 2024). However, as highlighted in critical debates on AI and digital infrastructures, efficiency improvements do not eliminate the overall growth of computational demand documented in the literature. Four recurring design criteria emerge from the comparison: climatic integration, energy integration, infrastructural symbiosis, and resilient modularity. Climatic integration refers to the deliberate use of local environmental conditions (temperature, water availability, geology) to reduce mechanical energy loads. Energy integration denotes the sourcing of operational energy from context-specific renewable flows. Infrastructural symbiosis describes the capacity to exchange energy or material flows with adjacent urban or industrial systems (e.g., district heating). Resilient modularity indicates design configurations that support hardware upgrade, reuse, and decentralized deployment. These criteria suggest that energy-smart design should not be understood as isolated technical optimization, but as a systemic paradigm mediating between computational performance and environmental sustainability.

6 STRUCTURAL LIMITS, GOVERNANCE, AND FUTURE PERSPECTIVES

Despite its potential, the energy-smart design paradigm presents significant structural limitations. As noted in research on smart cities and sustainable digital infrastructures, technological efficiency does not automatically guarantee systemic environmental impact reduction (Bibri & Huang, 2025). Many analyzed solutions depend on geographically favorable conditions, hydropower availability, cold climates, district heating networks, which are not evenly distributed globally, raising concerns about international scalability. From a policy perspective, the growing energy footprint of data centers is prompting governments and international organizations to introduce regulations on energy efficiency and circular economy principles in IT infrastructures (Camocho et al., 2020). Yet many digital policies continue to frame AI primarily as a software phenomenon, overlooking infrastructural materiality and lifecycle impacts (Ghisellini et al., 2016). Corporate governance must balance performance, operational costs, and environmental responsibility (Jones, 2018), within a broader ecological transition involving environmental justice and resource redistribution issues (Borowy & Schmelzer, 2019). The risk of rebound effects remains significant: efficiency improvements may be offset by increasing computational demand, particularly in large-scale AI applications (Braidotti, 2019). Sustainability, therefore, cannot be reduced to technical optimization but requires deeper cultural and design reorientation (Latour, 2017; Taffel, 2016). Design assumes a strategic mediating role between technological innovation and planetary boundaries (Raworth, 2017). However, energy-smart design can only be effective if integrated within coherent energy policies, territorial planning instruments, and strategies for computational demand reduction, fully acknowledging

the materiality of digital infrastructure. Beyond individual design solutions, the energy-smart design framework has implications for territorial planning and digital infrastructure governance. Criteria such as climatic integration and infrastructural symbiosis can inform regional energy plans, zoning regulations for data center siting, and sustainability requirements in public procurement for digital services. At the European level, instruments such as the Energy Efficiency Directive and the European Green Deal provide regulatory frameworks within which these design criteria could be operationalized. Globally, the adoption of distributed, territorially embedded data center models could contribute to reducing digital infrastructure inequalities, supporting energy resilience in contexts beyond the Northern European geographies examined here.

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