Managing the Energy Demands of AI in Fragile Renewable-Based Power Systems

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2025 IEEE 6th KhPI Week on Advanced Technology (KhPIWeek) | 979-8-3503-8909-8/25/$31.00 ©2025 IEEE | DOI: 10.1109/KhPIWeek61436.2025.11288587

***Abstract*—This study addresses a growing tension in the digital sustainability discourse by quantifying the mismatch between AI-driven electricity demand and renewable energy supply. In response to recent calls for empirical studies, we introduce a dual-axis mismatch framework that structurally compares (1) the share of renewable electricity in global generation and (2) the share of that renewable output consumed by AI. Drawing on a quantitative modeling approach and authoritative global data, we model electricity trends through 2030 under both Announced Policies and Net Zero scenarios. The results reveal that AI electricity demand is growing at nearly twice the rate of renewable generation, with AI potentially consuming up to 9% of global renewable electricity by 2030. To assess vulnerability, the study incorporates the April 2025 Iberian blackout as a case of low-inertia system failure under inflexible demand. Building on these findings, we propose the AI–energy alignment framework to guide strategic responses across technical, operational, planning, and governance domains. The study contributes a structural tool for anticipating digitally driven pressure on clean energy systems and supports resilience-focused energy management and infrastructure policy.**

***Index Terms*—sustainability, energy transitions, AI energy demand, renewable power systems, resilience, energy systems management.**

I. Introduction

In recent years, artificial intelligence (AI) has emerged not only as a key enabler of energy efficiency and grid optimization, but also as a rapidly growing source of electricity demand. As AI adoption accelerates, particularly through large-scale data centers, real-time learning systems, and generative models, the sector's electricity requirements are projected to rise exponentially. This growth introduces a new layer of pressure on energy systems that are simultaneously attempting to decarbonize and digitize [1], [4], [13], [17].

At the same time, renewable-based power systems, central to the global energy transition, face well-documented challenges related to intermittency, low inertia, and flexibility [3], [11]. While renewables reduce emissions, their integration can compromise system stability when not matched with adequate storage, balancing services, or flexible loads. As AI workloads tend to be always-on and geographically concentrated, they increase baseline demand and reduce the system's ability to buffer volatility. If unmanaged, this interaction may lead to systemic instability, including blackout risks [7], [13].

Despite growing awareness of AI's energy footprint, empirical analyses that quantify its impact relative to renewable electricity supply remain scarce. Even fewer studies link these dynamics to real-world system vulnerabilities or offer concrete frameworks for aligning digital expansion with energy resilience [12], [13], [17].

To address this gap, the study draws on empirical data from Statista [2], IRENA [3], and the IEA [4] to model the trajectory of AI electricity demand and renewable electricity generation from 2022 to 2030. We examine two global development paths: IEA's Announced Policies Scenario and Net Zero by 2050 Scenario, to assess the pace and scale of this mismatch. The central question guiding our analysis is how the growing electricity demand from AI workloads can be quantified in relation to renewable energy supply, and what strategic responses are required to safeguard the resilience of renewable-based electricity systems.

The paper proceeds in four steps: it first models AI electricity demand and renewable generation growth through 2030; second, calculates the mismatch using scenario-based projections and compound annual growth rates (CAGR); third, assesses system vulnerabilities linked to digital load pressures; and finally, introduces the AI–Energy Alignment Framework, a strategic tool for coordinating technical, operational, and policy-level responses to digitally induced energy stress.

II. Theory And Research Question

The intersection of AI and renewable energy has generated increasing research interest, particularly in the context of digital-led sustainability transitions. A recent Scopus search reveals that more than 90 peer-reviewed papers were published in Business and Management journals in 2025 alone, specifically addressing AI's role in energy, infrastructure, and sustainability contexts. This surge reflects a growing recognition that digitalization is not only shaping how energy systems are managed, but also redefining their structural constraints and vulnerabilities.

The International Energy Agency (IEA) frames AI as a transformative force with the potential to enhance energy system flexibility, improve demand forecasting, and support the integration of variable renewables [1]. In line with this, recent studies have demonstrated how AI technologies can optimize grid operation and renewable deployment, especially in forecasting and system control domains [14], [16].

Beyond its enabling role, AI is also emerging as a source of growing electricity demand, with widespread implications for energy system balance. This "energy hunger paradox," as defined by Senyapar and Bayindir [13], captures the dual nature of AI as both a sustainability enabler and an energy-intensive 'consumer'. According to the IEA [4], global electricity demand from AI workloads is projected to rise sharply by 2030, driven by the rapid growth of generative models, data centers, and edge computing infrastructure. Yet, despite these trends, few studies quantify this demand in relation to projected clean energy supply or examine its implications for system resilience.

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Existing contributions to AI and energy research tend to focus on AI for energy optimization [15], AI patent activity and policy interaction [16], or green innovation pathways [12]. Raza and Shakeel's text-mining analysis [18] confirms that electricity consumption and low-carbon energy transitions are central to current debates, yet does not disaggregate AI's direct impact. Similarly, broader policy outlooks [8], [9] and scenario-based modeling efforts [4], [3] emphasize decarbonization targets without accounting for emerging digital loads.

These gaps persist even in recent policy outlooks that prioritize electrification, green hydrogen, and renewable expansion, giving at the same time limited attention to the rising impact of digital infrastructure on grid fragility [10]. While some frameworks emphasize structural transformation in support of renewables [11], [17], [25], they do not account for the surge in AI-driven demand and primarily treat it as a solution, not as a source of additional system pressure.

The systemic dimension of this imbalance becomes increasingly visible when viewed through the lens of infrastructure coordination and planning. Industry analysis from S&P Global [7] notes that data center deployment is accelerating faster than power system development, with facilities reaching 1 GW scale and often being constructed ahead of confirmed grid capacity. These trends, combined with permitting delays, limited demand flexibility, and fragmented policy frameworks, raise critical questions about how resilient renewable-based systems will be under growing digital load pressure.

Addressing this emerging challenge, our paper responds directly to recent calls for empirical research that quantifies AI's energy implications and system-level risks in the context of global sustainability targets [13]. Whereas this work has focused on conceptual trade-offs and policy alignment, our analysis quantitatively assesses the mismatch between projected AI electricity demand and renewable energy generation capacity. We extend the debate from theoretical sustainability alignment toward concrete system resilience concerns by modeling this energy imbalance and evaluating its implications for grid stability, including blackout risks. By answering the research question "How does the growing AI electricity demand challenge the resilience of renewable-based power systems, and what managerial responses can guide strategic alignment?", we also contribute a novel dual-axis mismatch framework that can inform interdisciplinary energy planning at the intersection of AI growth and clean energy transitions.

III. Methodology

Our study adopts a mixed-method approach that combines a narrative review of emerging interdisciplinary literature with scenario-based quantitative modeling. The theoretical background is developed through a narrative review aligned with the principles of emerging topics research. Relevant literature on digital energy demand, renewable grid fragility, and infrastructure resilience was examined to identify gaps in existing frameworks. This review helped us to conceptualize the dual-axis mismatch framework, which guides the empirical components of the study.

The empirical modelling was based on publicly available datasets from the IEA [1], Statista [2], and the International Renewable Energy Agency (IRENA) [3]. We model electricity demand from AI workloads and electricity generation from renewables for the period 2022–2030, under both the IEA's Announced Policies Scenario (APS) and Net Zero by 2050 Scenario. Projections are based on reported capacity data, assumed technology-specific capacity factors, and standard energy modeling equations.

Renewable electricity generation is estimated by converting capacity figures (in gigawatts, GW) into energy output (in terawatt-hours, TWh) using the standard energy generation formula [4]:

$$\text{TWh} = \text{GW} \times \text{Capacity Factor} \times \text{Hours/Year} \div 1{,}000, \quad (1)$$

GW - installed capacity in GW; Capacity Factor - share of time the plant operates at full output (varies by technology); Hours/Year = 8,760.

Electricity consumption for AI by data centers is determined based on projected electricity use volumes and regional distribution of data center infrastructure [21], [22].

To evaluate the intensity of change over time, we apply the Compound Annual Growth Rate (CAGR) formula:

$$\text{CAGR} = \left(\frac{\text{Final Value}}{\text{Initial Value}}\right)^{\frac{1}{n}} - 1\,, \quad (2)$$

n - number of years.

To assess systemic vulnerabilities, we incorporate the April 2025 Iberian blackout [5], [6] as a real-world case study illustrating grid vulnerability under high renewable penetration and inflexible digital loads. This is supported by industry insights from S&P Global on data center growth patterns [7], permitting bottlenecks, and infrastructure coordination failures.

IV. Findings and Implications

To answer the research question, we begin by modeling the global electricity demand from AI workloads and comparing it to both total global electricity generation and renewable electricity output. Table I presents the trajectory of AI electricity demand from 2022 to 2030, and Table II outlines the growth in global installed renewable capacity. Using this capacity data and technology-specific capacity factors, we estimate renewable electricity generation through 2030 in Table III.

TABLE I
AI Energy Demand (2022–2030)

Year	Global AI Electricity Demand (TWh)	% of Global Demand	Notes
2022	~460	~2.0	Baseline year, includes general data center use
2026	~1000	~3.5 - 4.0	Projected doubling, driven by generative AI, cloud, and crypto
2030	~1,500-2,000	~4.5 - 6.0	Continued exponential growth, mostly from AI workloads

Source: Compiled by the authors based on [1], [2].

TABLE II
Renewable Energy Capacity Growth (2022–2030)

Year	Global Installed Renewable Capacity (GW)	Annual Additions (average, GW)	Cumulative growth
2022	~3,396	~318 (actual)	Baseline year [3]
2024	~4,300	~452	~27% increase from 2022 [1]
2026	~5,800	~750	~71% increase from 2022 [1]
2030	~7,902	~525	~133% increase from 2022[4]

Source: Compiled by the authors based on [1], [2], [3], [4].

Following the trajectories in Tables I–III, we observe two concurrent but diverging trends. While AI electricity demand is projected to more than quadruple by 2030, renewable electricity generation is expected to grow by only about 2.5 times. Despite improvements in capacity and efficiency, clean energy supply is not keeping pace with accelerating AI-driven demand. This imbalance suggests a potential structural paradox within the energy transition.

TABLE III
ESTIMATED RENEWABLE ELECTRICITY GENERATION BASED ON CAPACITY (2022–2030)

Year	Global Installed Renewable Capacity (GW)	Assumed Average Capacity Factor**, %	Estimated Generation (TWH)	Calculation*
2022	~3,396	32	~9,510	3,396 × 0.32 × 8,760 /1,000
2024	~4,300	33	~12,460	4,300 × 0.33 × 8,760 / 1,000
2026	~5,800	34	~17,320	5,800 × 0.34 × 8,760 / 1,000
2030	~7,902 / ~7,442	35	~24,228/ ~22,817***	7,902 × 0.35 × 8,760 / 1,000/ 22,817/[0.35 × 8,760 / 1,000]

Source: Compiled by the authors based on [20].

Notes: *based on the standard energy generation formula (1);
**based on (IEA, IRENA) the capacity factors increase slightly to reflect improved efficiency, digital controls, and wider deployment in high-resource areas: wind (onshore/offshore avg) - 30-40%; solar PV (utility-scale) 15-25%; hydro (global average) - 40-50%; biomass/geothermal - 60-80%; global average (combined)~30-35%.
***the target is based on the IEA [19].

To assess the depth of this divergence, we compare average growth rates for AI electricity demand and renewable electricity generation using the compound annual growth rate (CAGR) method ((2), Table IV).

TABLE IV
IDENTIFYING THE MISMATCH BETWEEN AI ENERGY DEMAND AND ESTIMATED RENEWABLE ELECTRICITY GENERATION (2022–2030)

Metric	2022	2030	CAGR (2022–2030)
AI Electricity Demand (TWh)	~460	~2,000	~20.3%
Renewable Electricity (TWh): Announced Policies Scenario (APS)	~9,510	~24,228	~12.4%
Renewable Electricity (TWh): "Net Zero" projection	~9,510	~22,817	~11.6%

AI electricity demand is growing nearly twice as fast as renewable electricity generation. Even under the IEA Net Zero by 2050 scenario, which assumes aggressive renewable expansion, the pace of AI growth outstrips clean energy supply. This confirms a strategic mismatch: if left unmanaged, AI/data center electricity consumption could erode the sustainability benefits of renewable deployment.

To illustrate the implications of this imbalance, we introduce the dual-axis mismatch framework as a structural approach to evaluating energy system fragility in the face of sector-specific demand surges. The framework plots two interdependent dimensions:

(1) the share of renewable electricity in total generation (a measure of systemic progress),

(2) the share of renewable electricity consumed by a single sector, in this case AI (a measure of sectoral load pressure).

This dual representation allows for the assessment of whether a sustainability transition is not only progressing in absolute terms, but also whether it is being undermined internally by high-growth, high-consumption sectors.

Figure 1 compares these two dynamics: the share of renewables in global electricity generation (left axis) and the share of those renewables that would be consumed by AI workloads alone (right axis). While renewables may supply over 60% of electricity by 2030, AI could absorb up to 9% of this clean energy, effectively internalizing a growing pressure within the energy transition itself (Fig.1).

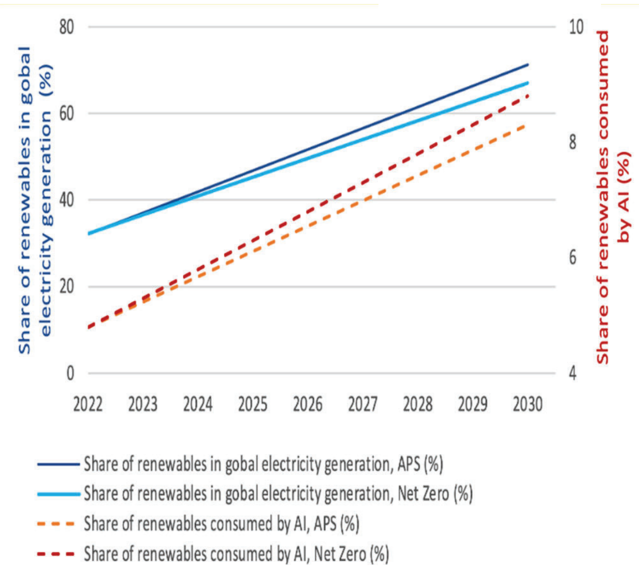

Fig.1. Projected mismatch of renewable supply and AI demand, 2022–2030 (authors' estimations)

To further explore the spatial dimensions of this imbalance, we disaggregate projections by region, focusing on the United States (USA), China, and the European Union (EU) – three of the largest AI infrastructure hubs. The analysis was conducted based on the calculations of the expected renewable electricity production by regions of data center location (Table V) and scenarios for forecasts of electricity consumption by these centers (Table VI). This geographic clustering of AI-driven demand (Tables V–VI) reveals even more pronounced mismatches between digital load growth and renewable electricity availability.

TABLE V
ESTIMATED RENEWABLE ELECTRICITY GENERATION BASED ON CAPACITY BY REGION OF DATA CENTER LOCATION (2023–2030)

Year	Global Installed Renewable Capacity (GW)	Assumed Average Capacity Factor**, %	Estimated Generation (TWh)	Calculation*
2023				
USA	0,385 [1, c. 5]	32,5	~1,096	0,385×0.325×8,760/1,000
China	1,454 [1, c. 3]	32,5	~4,140	1,454×0.325×8,760/1,000
EU	0,631 [1, c. 4]	32,5	~1,796	0,631×0.325×8,760/1,000
2030				
USA	0,938 [2]	35,0	~2,876	0,938×0.35×8,760/1,000
China	2,461 [2]	35,0	~7,545	2,461×0.35×8,760/1,000
EU	1,236 [2]	35,0	~3,790	1,236×0.35×8,760/1,000

Source: Compiled by the authors based on [21], [22].

Notes: *to convert installed capacity (GW) into actual energy generation (TWh) for renewables, we used a standard industry approach based on capacity factors (1) [4].
**based on Table III.

While the mismatch between AI electricity demand and renewable electricity capacity presents a long-term sustainability challenge, it also introduces more immediate risks to system resilience, particularly the rising likelihood of blackouts. As AI workloads concentrate in energy-intensive data centers that operate continuously and with limited flexibility, they contribute to sharp increases in baseline demand. In parallel, the growing share of renewables (especially wind and solar) reduces grid inertia and weakens the system's ability to respond to fluctuations or disturbances. Without sufficient storage, flexible backup, or smart demand management, these dynamics can lead to cascading failures. A stark illustration of this occurred on April 28, 2025, when Spain and Portugal experienced one of Europe's largest power outages. In under five seconds, Spain lost approximately 15 gigawatts of generation capacity (about 60% of its total supply) [5].

TABLE VI
IDENTIFYING THE MISMATCH BETWEEN AI ENERGY DEMAND AND ESTIMATED RENEWABLE ELECTRICITY GENERATION BY REGION OF DATA CENTER LOCATION (2023–2030)

Metric	2023	2030	CAGR (2023–2030)
USA			
AI Electricity Demand (TWh)	~148 [1, p.35]	~388 [2, p.64]	~14.8%
		~860*	~28.6%
		~1,050 [1, p.22-24]	~32.3%
		~1,050 [1, p.22-24]	~32.3%
Renewable Electricity (TWh)	~1,096	~2,876	~14.8%
China			
AI Electricity Demand (TWh)	~90 [1, p.35]	~265 [2, p.64]	~16.7%
		~588*	~30.7%
		~1,000 [1, p.27]	~41.1%
Renewable Electricity (TWh)	~4,140	~7,545	~9.0%
EU			
AI Electricity Demand (TWh)	~68 [1, p.35]	~113[2, p. 64]	~7.5%
		~252*	~20.5%
		~265 [1, p. 24]	~21.4%
Renewable Electricity (TWh)	~1,796	~3,790	~11.3%

Source: Compiled by the authors based on [23], [24].

Notes *to calculate electricity consumption by data centers, we used data on the total demand for electricity from AI in 2030 (~2,000 TWh (Table IV)) and a forecast of the structure of electricity consumption for AI data centers in the United States, China, and the EU in 2030 ([24, p. 64]):

2,000×0.43=866 TWh (USA).

2,000×0.294=588 TWh (China).

2,000×0.126=252 TWh (EU).

The blackout disrupted transportation, communications, and essential services, affecting nearly 60 million people. Preliminary investigations suggest that the incident was triggered by abrupt disconnections in generation, possibly linked to the volatile nature of renewable energy sources and the lack of mechanical inertia in the grid [6]. This case has highlighted the need for grid stabilizers, increased storage, and better international connections to prevent such occurrences in the future. The convergence of inflexible digital loads and fragile clean energy grids thus poses not only an environmental paradox but also a critical reliability risk for electricity systems worldwide.

Recent industry analysis [7] further supports this view, revealing that speculative AI infrastructure development is outpacing the expansion of underlying power systems. According to S&P Global data, AI-driven data centers now demand up to one gigawatt per campus, ten times the scale of previous deployments, yet permitting timelines for grid connections can lag by several years. These facilities, often built ahead of confirmed power availability, place additional stress on already low-inertia grids and complicate load forecasting. Moreover, while AI data centers may offer flexible load profiles in theory, existing business models rarely prioritize energy adaptability. Without stronger coordination between data center developers and power infrastructure operators, such unchecked digital growth may undermine grid stability, particularly in regions already struggling to integrate high shares of variable renewables.

V. DISCUSSION, CONCLUSIONS, AND LIMITATIONS

Building on the empirical findings and the blackout risk case, we propose the AI–energy alignment framework to structure multi-level strategic responses to sector-driven pressure on clean energy systems. It links observed vulnerabilities (mismatch between AI demand and renewable supply, geographic clustering of AI infrastructure, inflexible AI workloads, blackout risk from high volatility and low inertia, disjointed policy between AI and energy system) with strategic entry points for mitigation across technical, operational, planning, engineering, regulatory and governance levels (Table VII).

TABLE VII
STRATEGIC RESPONSES TO MANAGE THE RISING AI ELECTRICITY DEMAND IN FRAGILE RENEWABLE-BASED POWER SYSTEMS

Systemic Challenge	Empirical Insight	Strategic Response	Level of Intervention
Mismatch AI demand vs. renewable supply	AI demand grows at ~20% CAGR vs. ~12% for renewables; AI may consume up to 9% of renewable electricity	Energy-aware AI infrastructure design (e.g., efficiency standards, carbon-aware scheduling)	Technical / Corporate[1]
Geographic clustering of AI infrastructure	Data center concentration amplifies local fragility and transmission stress	Location-based planning incentives; zoning AI infrastructure near grid-stable or dispatchable sources	Planning / Regulatory[2]
Inflexible AI workloads (baseline load pressure)	AI data centers operate 24/7, increasing baseline load and reducing flexibility	Workload deferral strategies; integration with demand-side response mechanisms	Operational / Digital[3]
Blackout risk from high volatility + low inertia	Iberian blackout illustrates instability under high renewables + inflexible demand	Grid-forming inverters, hybrid energy storage, synthetic inertia, localized balancing units	Engineering / Grid Planning[4]
Speculative growth and infrastructure lag	AI data centers are rapidly scaling to >1 GW campuses, often before grid capacity is confirmed	Require payment for grid reservation, reform permitting, and prioritize partnerships with established providers	Regulatory / Market Design[5]
Disjointed policy between AI and energy systems	Current policies treat digital and energy sectors in silos	Integrated digital-energy policy frameworks; scenario-based digital growth planning aligned with capacity	Governance / Strategic Foresight[6]

Source: Compiled by the authors.

Notes:
[1] *Engineering and design solutions managed at the firm level.*
[2] *Spatial planning, permitting, and regional development policy.*
[3] *Real-time load control and software-based flexibility.*
[4] *Physical infrastructure and system architecture upgrades.*
[5] *Rules for grid access, pricing, and collaborative incentives.*
[6] *Long-term, cross-sector coordination and policy integration.*

These responses address critical gaps in prior research, which has highlighted AI's value for grid forecasting and optimization [14], [15], but has largely overlooked its growing electricity demand and its role in loading renewable power systems. Following Senyapar and Bayindir's [13] call for an empirical understanding of the energy footprint of AI, we model the rate at which AI-driven electricity demand outpaces renewable supply and present this tension as a structural paradox. In doing so, we introduce a dual-axis mismatch framework that links energy system progress with internal pressures from digital expansion. Our contribution reframes AI not just as a sustainability enabler, as emphasized in [16], but as an accelerating, and often unmanaged, consumer of clean energy. This dual role has received limited empirical attention, particularly regarding blackout risks and infrastructure misalignment. By segmenting demand across the U.S., China, and the EU, we also highlight regional differences that extend current policy-focused studies.

Our AI-energy alignment framework provides a structured tool for managerial decision-making in policy, utility planning, and digital infrastructure development. By matching system-level challenges with targeted responses at six levels of intervention, it enables cross-sector coordination and supports efforts to align AI-driven growth with energy resilience under tightening sustainability targets.

We acknowledge several limitations in this study, including the use of extrapolated data and scenario-based assumptions from international sources, which may not fully reflect the pace of change in AI hardware efficiency or shifts in regional policy. Future research could build on this work by incorporating real-time load profiles, lifecycle emissions of AI models, or bottom-up assessments of demand flexibility.

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