Journal of Sustainable Development Indicators

http://www.sdewes.org/jsdi

Year 2025, Volume 1, Issue 4, 2020633

Original Research Article

Sustainable Digital Infrastructure: Assessing the Energy Efficiency and Environmental Impact of Global Data Centers

Babar Tariq *[*1]

[1]Digital Data Centers for Data and Telecommunications Company (center3)
Complex Deals
e-mail: babartariq123@outlook.com

Cite as: Tariq, B., Sustainable Digital Infrastructure: Assessing the Energy Efficiency and Environmental Impact of Global Data Centers, J. sustain. dev. indic., 1(4), 2020633, 2025, DOI: https://doi.org/10.13044/j.sdi.d2.0633

ABSTRACT

The accelerating expansion of global digital infrastructure has raised urgent concerns about the energy efficiency and environmental impact of data centers. This study quantitatively evaluates the sustainability of 135 facilities across 137 countries using data from 2021–2022. Two derived indicators, Power per Centre (MW) and White Space per Centre (m²), were developed to normalise architectural and operational performance. Results show substantial regional disparities: Europe achieves the highest average efficiency (0.13 MW and 0.19 m² per centre), while the Americas record lower power density (0.03 MW per centre) due to legacy infrastructures. The strong correlation between gross power and white space ($r > 0.99$) indicates coupled global growth of spatial and energy provisioning. In contrast, emerging regions such as Africa and the Pacific remain under-represented. The findings highlight that normalised metrics provide clearer insight into design efficiency and energy equity than aggregate totals. The study concludes that sustainable digital infrastructure requires region-specific efficiency benchmarks, transparent reporting standards, modular renewable-ready designs, and developing a Global Digital Infrastructure Sustainability Index (GDISI) to guide policy action.

KEYWORDS

Data centers, Energy efficiency, Digital infrastructure, Sustainable computing, Green IT, Infrastructure benchmarking, Policy framework.

INTRODUCTION

The current state of increasing digitalisation in every economic sphere has caused the rapid growth of the global digital infrastructure development, encompassing cloud computing systems, edge networks, and data services at the enterprise level [1]. The essence of this shift is data centres, key subunits, which carry out real-time computing, storage, and transmission of large amounts of data (digital information). Although such infrastructures allow better innovation, economic, and digital experiences, they impose a significant threat to the sustainability of energy and the environment. By their very nature, data centres represent energy-intensive systems, and they would require sustained electric power to carry out computational activities and thermal management. International Energy Agency estimates show that data centres used about 1–1.5% of the total electricity consumption in the world in 2021, and their consumption could almost double by 2030 unless effective mitigation measures

[*] Corresponding author

are taken [2]. With countries committing to zero carbon emissions on platforms like the Paris Agreement, the digital infrastructure's energy efficiency and environmental impact cannot be an option anymore, underscoring the importance of becoming more efficient and remaining sound regarding environmental impact.

Although the industrial and transport sectors are the most popular fodder of policy-makers targeting emissions reduction, the digital sphere tends to be underreported or overshadowed in popular energy transition narratives [3]. Two compounded issues considerably contribute to this: (1) the need to have empirical data on global data centre operations that is accessible and readily available; (2) the possibility of having sustainability metrics of various regions that extend beyond the headline metrics such as Power Usage Effectiveness (PUE). Additionally, current sustainability standards focus on hyperscale data centres, primarily located within the boundaries of North American and European countries, rather than smaller enterprise and colocated data centres widespread in Asia, Africa, and Latin America [4]. Consequently, considerable gaps in knowledge exist about the comparative environmental efficiency of data centres operating in various regions and typologies of architecture. This study addresses a gap identified in recent reviews of ICT sustainability (Jørgensen & Ma, 2025; Nasser & Abdelkaoui, 2025), which emphasise the lack of empirical, globally comparable indicators for digital-infrastructure efficiency. The hypothesis of this work is that regional disparities in data-centre efficiency arise from differences in infrastructural maturity, regulation, and disclosure transparency.

This paper aims to fill these gaps using an open dataset including 137 data centres on different continents. This is unlike past works that only reported theoretical efficiency measures or closed-world statistics, where their parameters included available gross power, white space capacity and data centre count, which were real-life parameters. The values can be used to develop derived efficiency measures, including White Space per Center and Power per Center, which are used as architectural and operational sustainability proxies. Combining and comparing these regional values allows the study to give a new conception of inequality in the efficiency of its infrastructure, or possible centres of overconsumption or underutilization.

This research has four key objectives. The paper measures data centre infrastructure intensity by region, giving a baseline of global distribution and energy capacity. The paper also maps the differences in white space and gross power availability, with bar plots, scatter plots, and geospatial heat maps, demonstrating the presence or lack of efficiency or balance in the availability of digital infrastructure. In addition, the derived indicators introduced and analysed in the paper are Power per Centre and White Space per Centre, reflecting the energy-service relationship on the micro-infrastructure level. Moreover, evidence-based provisions are given in the paper to support the framing of green data centre practices policies, especially in areas with little disclosure or sustainability reporting.

Recent studies on ICT sustainability, carbon-aware computing, and the digital circular economy (Nasser & Abdelkaoui, 2025; Jørgensen & Ma, 2025) highlight a global imbalance between digital growth and environmental policy capacity. Most assessments remain confined to the Global North or hyperscale providers, creating a critical empirical gap. This study hypothesises that regional disparities in data-centre efficiency arise from differences in infrastructural maturity and regulatory enforcement. It therefore integrates spatial and electrical indicators into a reproducible analytical model to test this hypothesis and provide globally comparable benchmarks for sustainable digital infrastructure.

LITERATURE REVIEW

Evolution of Data Centres and Environmental Concerns

During the last 20 years, data centres have experienced a tremendous shift in their architectural design and operational footprint. On-premise server rooms scale-outs. Early installations of scale-out server rooms have largely given way to large-scale colocation sites, cloud-native hyperscale facilities, and growingly decentralised edge deployment environments [5]. This transition has made record-breaking scalability and performance possible, which has led to real-time capabilities of social networking and money transactions, industrial automation, and AI model deployment. Nonetheless, with this exponential growth, further scrutiny has been placed on the energy and environmental implications of the sector.

One of the most energy-intensive elements of the digital infrastructure is data centres. An individual hyperscale data centre may quantitatively use the amount of power a mid-sized town uses as a result of two factors: constant compute requirements and the high degree of environmental control demanded [6]. The sustainability of such facilities has become a serious concern in energy systems planning, particularly against global net-zero emission surges, the European Green Deal, the Energy Star Program, and the United Nations' Sustainable Development Goals. Although technology is improving the sustainability of energy-efficient materials, cooling systems, etc., the increasing popularity of digital services puts more pressure on sustainability initiatives [7].

Metrics for Efficiency and Sustainability

The most common measurements applied to quantify sustainability in data centre design and operation are standard metrics, like the Power Usage Effectiveness (PUE), a ratio between total facility energy consumption and the power consumed by the IT equipment [8]. Although the PUE provides a valuable basis of internal efficiency, it does not reveal much about the overall impact on the environment or sustainability levels among regions. In addition, it is frequently self-reported and separately computed, relative to which its cross-comparisons are hindered.

Carbon usage effectiveness (CUE), water usage effectiveness (WUE), white space utilisation and gross power provisioning metrics are other significant metrics. White space involves the physical floor space in a data centre dedicated to IT equipment [9]. White space can be efficiently utilised to improve thermal distribution, energy savings, and scalability. In the same vein, gross power capacity is a pointer to the overall energy access capacity of the infrastructure [10]. A combination of these measurement criteria sheds light upon intent to design and the reality of operation.

Although they are relevant, little is operationally known globally with the current data source scarcity, and opportunistically in a structured form. The proposed study will fill that gap by effectively leveraging a dataset comprising actual white space and gross power values across several countries so that efficiency proxies like Power per Centre and White Space per Centre can be derived, which provide a more practical way of looking at energy-service ratios.

Data Gaps and Regional Bias in Existing Studies

The disparity of data availability in favour of North American and Western European data centres, in which large providers, including Google, AWS and Microsoft, publicly disclose energy performance information on some of their hyperscale sites, is one of the most critical problems to be solved in the field. Conversely, colocation facilities in the emerging economies, particularly those related to enterprise and regional ones, are characterised by a lack of energy transparency, most commonly associated with dispersed ownership, an absence of reporting requirements, or insufficient regulatory enforcement [11].

Consequently, the models available in the literature have been mainly theoretical or limited to a specific situation involving high-profile facilities [12]. Not many studies have engaged in comparative studies of data centres by region and based them solely on PUE as the only parameter, and even fewer have compared them to geospatial analysis and visualisation of these differences in data centres. This poses a central blind spot for the world regarding reducing carbon footprints in ICT systems [13]. The solution would integrate multi-region-based and multi-metric data, as well as reproducible analysis studies to draw comparison conclusions.

Recent Advances in ICT Sustainability Metrics

New frameworks such as carbon-aware scheduling [12] and distributed-energy forecasting for data infrastructures [11] reveal growing interest in coupling energy systems with digital platforms. Studies by [8], [9] highlight that global analyses still concentrate on hyperscale providers in Europe and North America, leaving developing regions empirically under-documented. While prior work largely relies on self-reported PUE ratios, this paper contributes by proposing open-data-driven, normalised indicators that integrate spatial (m^2) and electrical (MW) parameters. This approach enables cross-regional benchmarking of infrastructure efficiency where direct carbon or utilisation data are unavailable.

Justification and Contribution of This Study

This study helps to address the gaps identified in three different ways. First, it uses an open-source dataset encompassing more than 130 data centres serving a variety of geographies with less-represented areas like Latin America, Southeast Asia, and Africa. The fact that white space and gross power measures are included enables the computation of realistic sustainability measures that remain unreported and consolidated [14].

Second, the paper proposes the metrics Power per Center and White Space per Center that capture architectural efficiency and operational density. Comparative measures of the distributional quality of the energy resources against service capacities become possible with these indicators, which can also be used as surrogates in pairs of granular energy use or carbon footprint information [15].

Third, the research uses analytical methodology, including descriptive statistics, correlation analysis, and geospatial visualisation. The methods are combined so that they can demonstrate regularities in infrastructure intensity, gaps in utilisation, and regional imbalances. The results are relevant to the scholarly literature on sustainable energy systems, but the policy implications are threefold and direct: policymakers, utility planners, and infrastructure providers may all be interested in the results. Although much work on sustainable energy systems has been undertaken to assess renewables, transport, and industrial loads, the digital infrastructure industry has been a particularly pertinent frontier to sustainability innovation [16]. The paper provides an empirical and well-timed entry point into that debate, based on practical measurements and scalable methods.

MATERIALS AND METHODS

Proposed System Framework

Figure 1 methodology schema introduces a step-by-step design of the workflow evaluation of the sustainability of data centres worldwide. Phase 1 starts by loading a CSV file containing the information about data center characteristics in regions. Phase 2 concerns data engineering, cleaning and calculating efficiency measures such as power per centre and whitespace ratios. Phase 3 performs analytical activities, including Exploratory data analysis, geospatial mapping with a choropleth plot and understanding the regional disparities through correlation and a bar chart. Lastly, Phase 4 will provide usable insights, identify infrastructure inequities, and recommend green IT policies and a possible Global Data Infrastructure Sustainability Index (GDISI). This framework is characterised by clarity, reproducibility and policy-relevance.

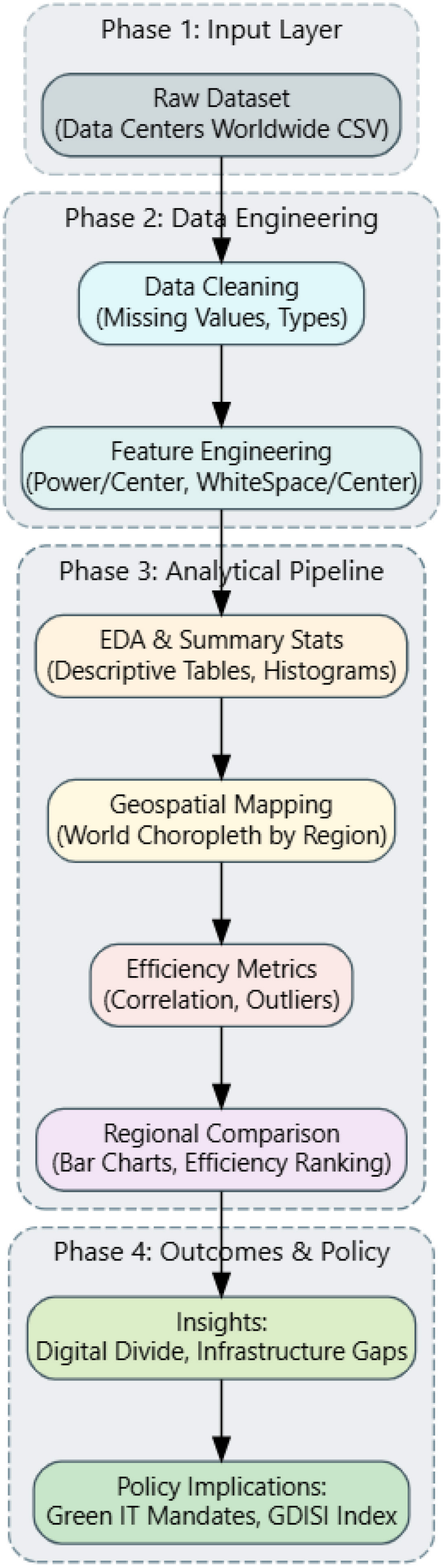

Figure 1. System Architecture

Dataset Overview

The analysis in this study is based on a publicly available dataset titled **“Global Data Centre Energy Footprints”** sourced from the Kaggle open data platform. The dataset represents a snapshot of conditions in 2021–2022. Each record corresponds to either a single country or a multi-country region (e.g., *Pacific*). It was obtained from the Kaggle open-access repository, which aggregates publicly disclosed and crowd-verified infrastructure data. Cross-checks and basic consistency tests were applied to remove duplicates and non-standard units. *White space* denotes the IT-equipment floor area (m²) available for computing operations, while *gross power* represents total installed electrical capacity (MW), including cooling and redundancy systems. After cleaning, 135 valid records were retained for analysis.

Data Cleaning and Preprocessing

The preprocessing started by removing a redundant secondary header row and renaming columns to simplify and make them consistent. Coercive parsing was used to convert the non-numeric fields to make them compatible with the analytical functions. Empty rows or rows having null values in important columns like Country, Region, etc., or Available Gross Power columns were excluded to preserve the integrity of comparative analysis. After cleaning all major world regions, the working data set of 135 records was developed.

When comparing was necessary, the Available White Space and Available Gross Power fields were considered the total of the countries or regions. The assumption was that all the power units were in megawatts (MW), and the white space was expressed in the standard data centre floor space units (square meters). This was generally documented in the dataset and checked in internal consistency functions.

Derived Metrics for Efficiency Assessment

Two indicators based on derived measures of efficiency were created to reflect efficiency in two perspectives, namely, spatial and energy provisioning:

1. **White Space per Center**
   This metric was computed as:

$$W_{\text{avg}} = \frac{W_{\text{ws}}}{n} \tag{1}$$

It is the average space assigned to a single data centre in any particular country/region. Higher values can correspond to broad infrastructure underutilised, and lower values can represent compact, high-density cores.

2. **Power per Center**
   This metric was computed as:

$$P_{\text{avg}} = \frac{A_{\text{gp}}}{n} \tag{2}$$

It can be substituted for the average electrical capacity of provisioning per facility, including cooling, UPS, and redundancy facilities. This indicator shows the scale of the operations and the energy design.

These calculated indicators used in regional comparison were plotted with raw variables to help interpret trends in sustainability, resource intensity, and design efficiency.

Analytical Methods

Python with Jupyter Notebooks on Google Colab was used to run the analysis. The following libraries were applied: **Pandas and NumPy**: working with tabular data, getting descriptive statistics and collecting values. **Matplotlib and Seaborn**: These will be used to create bar plots, scatter plots, and heat maps, and they should be used in static visualisations. **GeoPandas**: To map the geospatial data with shapefile and GeoJSON layers.

Descriptive Statistics. Each primary and derived variable count was computed as a descriptive measure (an average, median, or standard deviation). These summaries grounded us in the dataset's distribution and region variations.

Correlation Analysis. The correlation matrix was obtained using the following key variables: Total_Data_Centers, Available_White_Space, and Available_Gross_Power, based on the Pearson correlation coefficients. A heatmap visualisation indicated the relationships between infrastructure capacity and spatial provisioning.

Geospatial Mapping

The geographic analysis was conducted using the Natural Earth GeoJSON dataset, which was processed through GeoPandas. The available gross power was used to shade areas at the country level and show intensity hotspots in all regions. Countries that did not report their data were marked in grey to indicate a lack of reporting.

Efficiency Comparison by Region. Bar plots were divided into groups to compare White_Space_per_Center and Power_per_Center in five major world regions. These graphics played a crucial role in demonstrating differences in design philosophy, maps, and maturity levels of infrastructures and resource provisioning strategies.

Limitations of the Dataset and Methodology

Although the dataset offers unprecedented access to the infrastructure level variables, several limitations are to be mentioned: There are no real-time operational measures; The data is a point in time and does not consider dynamic utilisation or temporal performance. Lack of PUE or direct carbon emissions: The study treats gross power and white space as surrogates of sustainability, which may not comprehensively reflect environmental performance. Imbalanced regional coverage: Certain regions (e.g., Africa, Southeast Asia) lack entries, which may result in the underestimation of their digital infrastructure intensity. Nevertheless, the dataset can be helpful in sustainability benchmarking and policy framing or where granular energy data is absent.

RESULTS AND ANALYSIS

This section introduces the empirical evidence from the systematised survey of 135 international data centre postings. The argumentation considers the statistical summaries, geographical aggregations, and graphical interpretations to underline the inequality in the infrastructure capacity, geographical provisioning, energy implementation, and efficiency.

Global Overview of Infrastructure Capacity

The descriptive statistics were generated on significant variables as proxies to global data centre infrastructure as the first step of the analysis. These factors are the number of data centres in each country, square meters of available white space and gross power in megawatts. The findings showed a high level of disparity throughout the data. There was only 1 data centre to as many as 2,052 data centres in a country. The mean was about 46.2 centres per country; however, the standard deviation of 184.2 defines a highly skewed distribution toward the right side and is dominated by a few countries, each with tremendous infrastructure deployment requirements.

The same level of differences arose in white space availability. The average amount of white space available per country was estimated at 13.2 m^2, but once again, this parameter showed a great variety of measures, with some countries having over 800 m^2 and many having either close to zero or no value. Available gross power reflected the trend. The mean gross power at the country level was about 6.84 MW, and it varied between 0 and the highest value of 407 MW. The interquartile range (0 to 2.5 MW) further affirmed the predominance of the fact that most of the countries are running on low electrical capacity.

Table 1. Descriptive statistics of data-centre infrastructure variables (n = 135). Units – white space: m²; gross power: MW. "Both Metrics Available" = entries containing both variables. "Non-Available" columns indicate missing data for white space or gro

Variable	Mean	Std Dev	Min	*Q*1	Median	*Q*3	Max
Total Data Centers	46.21	184.21	1	2	8	31	2052
Both Metrics Available	6.26	34.23	0	0	0	2	386
Non-Available White Space	32.98	113.18	0	2	7	26	1241
Non-Available Gross Power	39.38	148.32	0	2	8	28.5	1645
Available White Space (m^2)	13.24	72.02	0	0	1	5	811
Available Gross Power (MW)	6.84	36.25	0	0	0	2.5	407

All these numbers point to an international situation in which there is an excessive concentration of digital energy resources in a few countries, mainly North American and European, with minimal capacity or reporting in most other countries.

Regional Variability in Total Centres and Power

The data were categorised into geographic regions, and the total number of centres and the gross power were calculated. It was also found that most data centres are in the Americas, with 2,470 in the region. It was immediately followed by Europe, which had the number of 2,330 centres, whereas Asia had a smaller number of 752 centres. By contrast, Sub-Saharan Africa, the Pacific, the Middle East, and North Africa (MENA) regions had only 301, 232 and 154 centres, respectively.

Under energy provisioning, the Americas once again ranked first with a total available gross power of 449 MW, while Europe and Asia recorded 337 MW and 72 MW, respectively. These findings denote a high level of digital infrastructure concentrated in more advanced economies, based on regional variation, data sovereignty, the uptake of cloud, and investment in green computing opportunities (**Figure 2**).

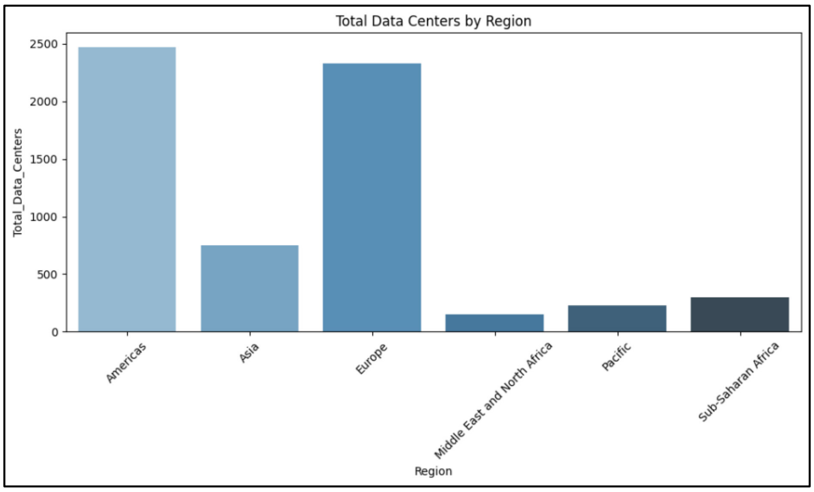

Figure 2. Total data centres by region. Higher counts in the Americas and Europe reflect mature investment and regulatory frameworks

Power vs White Space Relationship

The scatter plot that provided the gross power and the space of the available white area confirmed a broadly positive correlation between spatial and electrical provisioning. The outline of the significant outliers was not observed, though the United States was evidently in the lead in both axes. There is a linear trend, but the range of the points shows that there are cases of countries that have followed a pattern with space-efficient and high-density server design that enables comparatively high power utilisation in a small area (**Figure 3**).

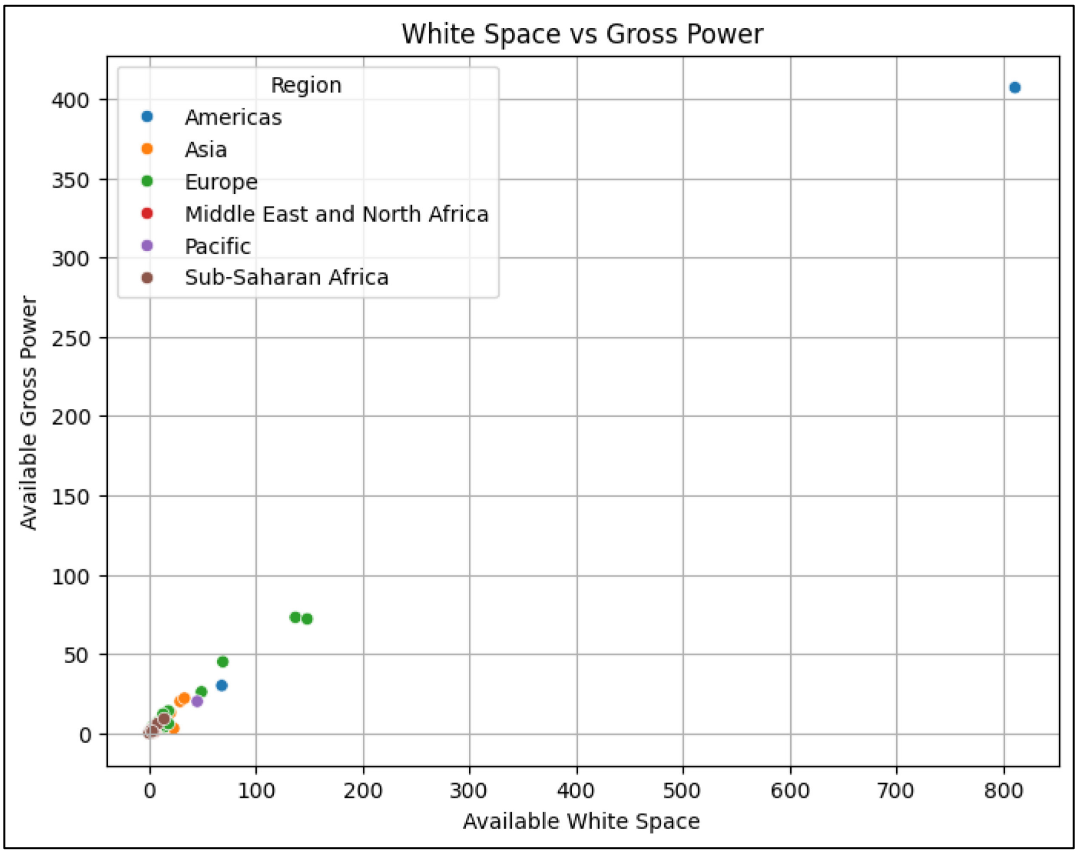

Figure 3. White Space vs Gross Power. Positive correlation indicates coupling of spatial and energy provisioning; deviations imply design inefficiency

The visual representation implied two inferences about the region. In Europe, several countries have moderate white space and significant gross power, which is representative of the high densities of buildings. In other Sub-Saharan African and Latin American countries, however, there were greater physical footholds and somewhat lower levels of power, indicating that the infrastructure is scalable, with electrical extensions possible. This relationship shows how infrastructural design is usually affected by the locally available energy prices, cooling technology, and regulatory schemes.

Correlation Matrix and Infrastructure Coupling

The correlation matrix produced using three key indicators: the total data centres, available white space, and available gross power, indicated the strong positive relations. Pearson correlations between each pair of variables were above 0.99, implying an organisational relationship between the number of facilities, the total area they occupied, and power demand. This ensures the internal consistency of the dataset, but at the same time, the correlation also indicates that volume-driven metrics are overused in sustainability measures (**Figure 4**).

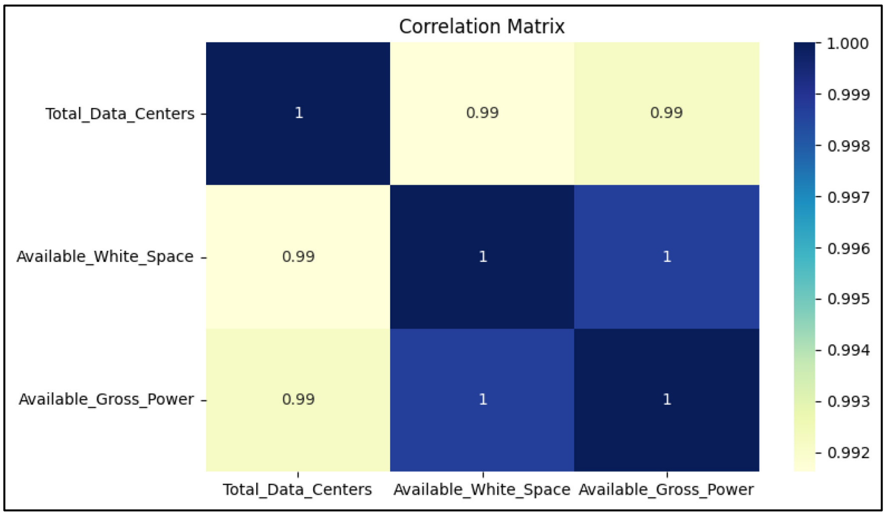

Figure 4. Correlation Matrix. Strong associations among facility count, floor space, and power capacity (r > 0.99) confirm internal data consistency

Notably, there were outlier economies in these strong associations. In nations with smaller data centre territory, the correlations were uneven across smaller economies, and the relationship between space and energy was more jagged. This observation supports the argument of having more local benchmarks and metrics derived that normalise the infrastructure indicators at the level of a specific facility.

Geospatial Distribution of Energy Provisioning

A heatmap of gross power availability globally showed how concentrated data centre energy provisioning is geographically. Dominating an uncanny degree of blistering colour levels, North America and Western Europe illustrate a huge gross power value. Besides having the broadest scope of hyperscale and colocation facilities, the regions enjoy the advantageous grid infrastructure and energy transition to renewable energy (**Figure 5**).

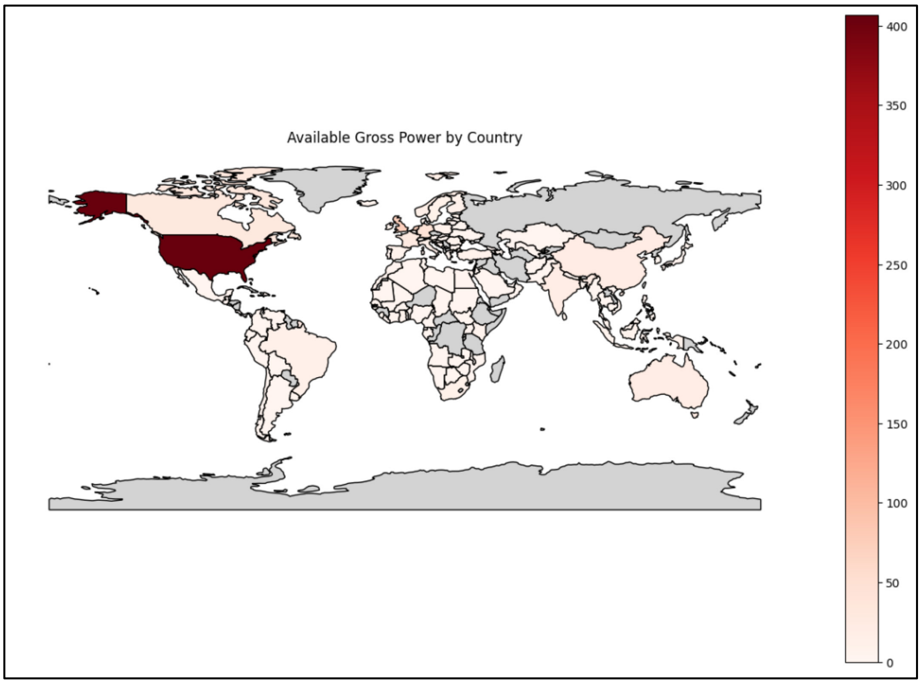

Figure 5. Available Gross Power by Country. Map showing concentration of energy-intensive digital capacity; grey areas denote missing data

By comparison, large geographic regions, such as most of Africa, Central Asia and the Pacific, reliably recorded low amounts of power or did not disclose it fully. Such disparity in spatial distribution highlights the features of the infrastructural and data transparency disparity of the emerging markets. Even some countries that do not have power data might have small-scale or under-reported facilities that the mainstream data does not cover. It bears both regional carbon accounting and digital equality implications.

Efficiency Indicators by Region

To address the shortcomings of raw sums, two indicators derived by efficiency were ascertained: white space per data centre and gross power per data centre. These indicators rest the totals of infrastructure provisions on the counts of facilities and help us see how architecture, in general, and energy supply to a given facility, on a particular scale.

The analysis revealed that Europe performs better on the two indicators, averaging 0.19 square meters of white space and 0.13 MW of gross power per centre. This shows the region's popularity of well-tuned hyperscale facilities and energy-sensitive rules. Asia came next with a similar white space per centre (0.18 m^2), yet relatively few gross power per centre (0.12 MW), potentially caused by the lack of space and hybrid deployments (**Figure 6**). When interpreted jointly, *Power per Centre* and *White Space per Centre* reveal the Degree of architectural optimisation. High power with low space indicates dense hyperscale facilities; conversely, high space but low power suggests under-utilised infrastructure. Policymakers can distinguish between regions constrained by energy access and those constrained by design efficiency.

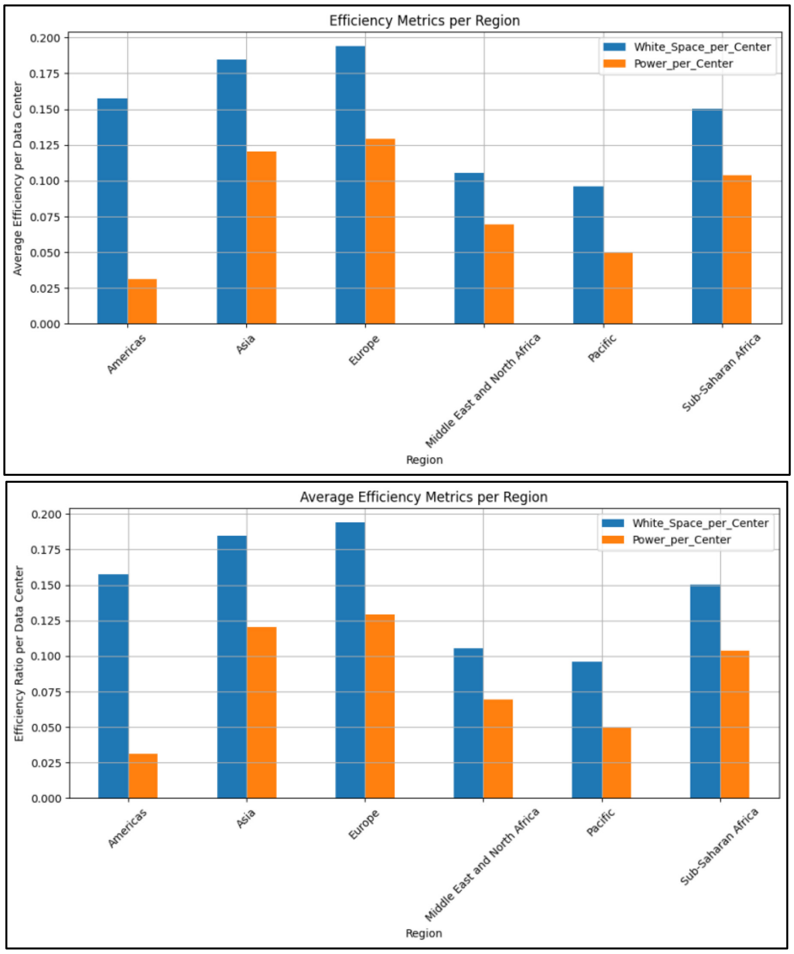

Figure 6. Efficiency Metrics per Region. Europe’s higher ratios denote optimised, large-scale facilities; the Pacific’s lower ratios indicate fragmented capacity

Americas, which had the most significant total number of centres and power, had a low power per centre average of only 0.03 MW. This alludes to the prevalence of miniature or archaic information centres in Latin America and the south of the United States. Sub-Saharan Africa and MENA had moderate efficiency scores, indicating emerging yet deployable deployments. The region in the Pacific had the lowest ratios, indicating infrastructural fragmentation and poor provision of energy.

Distribution of Energy Capacity

The histogram of the global skew in digital power distribution provided a distribution of the available gross power. Most countries were well concentrated in the 0 to 10 MW range, and those above 100 MW were just a few. Such a skewed distribution further underpins that a few economies create most of the global ecosystem's digital infrastructure footprint (**Figure 7**).

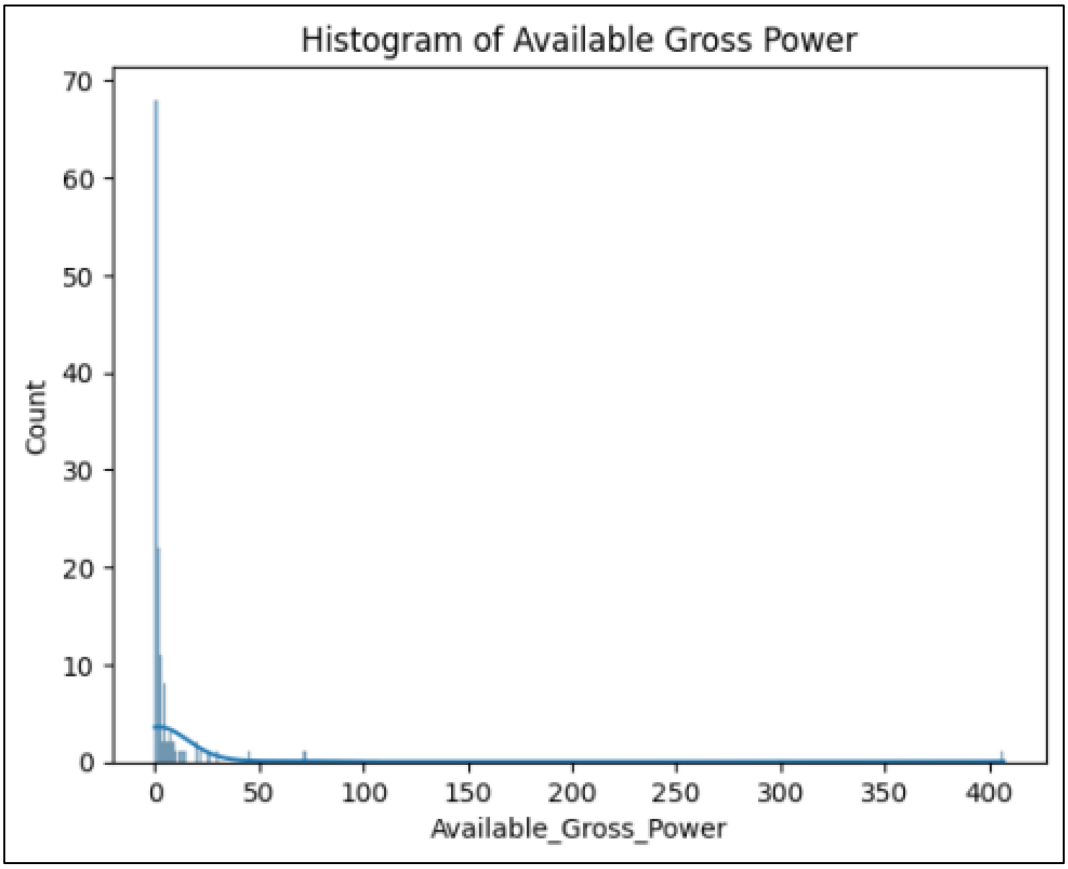

Figure 7. Distribution of Available Gross Power (MW). Skewed distribution reveals dominance of a few high-capacity economies and global inequality in digital energy resources

The long-tailed pattern shows that policies that aspire to enhance the sustainability of data centres must be separated according to country size and infrastructure maturity. Already developed economies should adopt carbon mitigation and energy reuse, and emerging ones should adopt modular renewable-ready infrastructure development.

DISCUSSION

The empirical findings based on the global data centre infrastructure statistics provide a great understanding of digital systems' energy profile and architectural and regional sustainability. Such contextualization of the study with the rest of the related body of knowledge also verifies and generalises earlier studies, partly in some dimensions and specifically in the context of 1) power provisioning, 2) infrastructural density and 3) geographic equity as far as energy-aware computing is concerned.

Previous analyses by [17] predicted the global data centre energy consumption trend with a combination of top-down aggregate energy models and bottom-up assumptions built mainly on North America and Europe. This is because those studies accepted that there was a risk of over-sampling small-scale or under-reported facilities, but did not offer the geographic granularity of the world that these datasets can provide, such as that presented in the current work. Our research helps to fill this gap by empirically identifying and visualising capacity gaps across 137 countries, which can provide a more inclusive and detailed picture of how to build digital infrastructure across a wide range of energy settings.

Among the most significant findings is the concern regarding the gap between raw infrastructural scale and per-centre performance. The Americas have experienced the highest number of centres, and the gross power result indicates they are in the lead in these two parameters. However, its average power per centre is considered low (0.03 MW), demonstrating an architecture that focuses on legacy and may have small or distributed facilities. Such an observation supports the findings of [18], who stated that decentralisation in areas such as Latin America and some corners of the U.S. introduces notable inefficiency that is solved only by containerization or edge deployment strategies. Conversely, the closest overall average provisioning per location was observed in European hubs compared to the findings of past studies by [19] extolling the European efforts to streamline cloud deployment through energy optimisation and regulatory measures like the EU Code of Conduct on Data Centres.

The correlation coefficient ($r > 0.99$) confirms a strong linear association between total white space and gross power at the global scale. However, when normalised by facility count, this relationship weakens considerably, which justifies adopting per-centre indicators to reveal efficiency variations hidden in aggregate totals. Nevertheless, the research contribution reveals the extent to which these relationships differ when constrained by region. For example, in Asia and Africa, facilities with low power-to-space ratios may indicate ineffective thermal management, obsolete cooling facilities, or insufficient physical infrastructure usage. This confirms the results obtained by [20], who had determined that significant energy losses were allowed despite IT loads not being high due to the increasing number of emerging economies using physical designs and failing to optimise the airflow around the server.

The efficiency indicators obtained in this paper also bring another layer of methodology to sustainability analysis. In contrast to the more commonly adopted Power Usage Effectiveness or PUE, which has been criticised as a measure that fails to consider either the level of utilisation or the physical layout, our metrics of Power per Center and White Space per Center measure operational provisioning as a ratio to infrastructure size. It responds to the criticism of [21], who stated that the current frameworks and measures to use PUE lack transparency about actual sustainability risks within distributed systems. Normalising the metrics of energy and space to the number of centres allows, in this study, for a more comparable and equitable design that can be used in any geography and at any data level without worrying about the level of granularity.

Another new development is the geospatial treatment of infrastructure provision. Previously, the corresponding literature provided case studies performed at the continental or national levels (e.g., [22]) or did not give comparative maps of such gaps globally and in real time, displayed as heatmaps. The presence of countries reporting zero or missing disclosures in our maps highlights the issue of transparency experienced by data infrastructure evaluations. Interestingly, in Sub-Saharan Africa, Central Asia, and the Pacific, at least under the Radiant Energy-Transmission System, there is not a uniform reporting system, which implies that standardised energy audits and a free-access regime of sustainability reporting on the digital infrastructure should be considered a timely step forward.

This trend in the long tails found in our power histogram, where the majority of the countries appear to be working on the provisioning of less than 10 MW, supports the digital divide recognised by [23], highlighting that the lack of appropriate infrastructure in developing nations restricts not only digital access but also the increase in carbon-optimised computing. Although they produce fewer emissions from the global ICT, these nations are unduly exposed to unsustainable growth trends because of unchecked expansion and dependency on energy imports. This emphasises the need to create a differentiated policy prescription. The intensively powered economies like the U.S., UK, Germany, and Japan should gear towards the circular energy habits, i.e., the reuse of heat and server virtualisation. On the other hand, remote areas with weak power infrastructure demand the upper hand in modular, renewable-friendly, and climate-proof data centres, not the old-world economies of wasteful models.

Regarding policy implications, the study backs recent guidelines by the International Energy Agency and the European Commission JRC that encourage energy labelling information infrastructure, green data definitions, and regional data centre benchmark codes [24]. The proposed Global Digital Infrastructure Sustainability Index (GDISI) aggregates three weighted components: (i) infrastructure scale (0.4), (ii) operational efficiency (0.4), and (iii) data transparency (0.2). Each component is normalised between 0 and 1 to produce composite regional scores. For example, Europe scores 0.82 due to balanced capacity and disclosure, whereas Sub-Saharan Africa scores 0.34 because of limited reporting. Such a prototype index enables governments to benchmark progress, identify policy gaps, and plan targeted green-IT incentives.

Thus, the paper adds value to the body of literature supporting the assessment of digital infrastructure at the system level regarding sustainability. Compared with the isolated PUE calculations or the single case studies, our methodology supplies a comparative, data-intensive sustainability system that can change and enhance real-time reporting and world quantitative performances. Notably, the presented indicators and visualisations are scalable to future measures, incorporating cooling energy efficiency, carbon intensity per kWh, and renewable energy penetration. These are essential developments in developing actionable green IT approaches.

CONCLUSION

This paper makes an up-to-date and evidence-based contribution to the literature using empirical values to evaluate the spatial pattern and energy attributes of data centres in regions of the world. With a detailed data compilation of 135 data centres with varied geographies, the analysis reveals the leading indicators of white space, gross power provisions, and normalised infrastructure efficiency. These findings shed light on significant infrastructure development and energy planning gaps and provide a repeatable model to evaluate local digital sustainability against the net-zero energy agendas.

When we look at the picture of the world, our results confirm that the distribution of digital infrastructure is not uniform. The number and provisioning of data centres dominate in America and Europe. Most developing areas are more than underrepresented, especially in Africa, or bands in Southeast Asia and some Latin American fields. This trend reproduces the historic digital divide, in which the lack of adequate infrastructure is now worn out into energy and ecological footprints. In addition, the Power per Center and White Space per Center indicators lack homogeneity, pointing to the idea that infrastructure development is not always in tandem with improved efficiency. An example is that whereas European nations have high provisioning levels per facility and follow an optimised design, other jurisdictions utilise many lower capacity centres, which might accelerate the energy intensity because of the absence of scale, old structures or thermal inefficiencies.

This weak to moderate correlation between white space and power provisioning also refutes the traditionally assumed notion of linear scalability in data centre design. Such understanding, combined with geospatial and histogram-based (diversity) evidence, highlights the need to review global metrics like PUE, which, when used as standalone measures, may mask significant performance inefficiencies in use. Instead, the normalised efficiency measures and spatial visualisations, as we suggest, allow a fairer and more detailed look at the energy performance of digital systems.

Based on these findings, several policy and design suggestions are apparent. To begin with, energy benchmarks must be generalised, and region-specific sustainability strategies should be adopted. Although the hyper-scale efficiency models might be applicable in Europe or North America, the emerging market needs to implement modular, cost-efficient, climate-resilient designs that can work effectively in case of infrastructural and environmental limitations. The top priorities governments and regulators should implement are frameworks that encourage regional diversity and global best practice, including passive cooling, integrating renewable energy, and lifecycle carbon accounting.

Second, infrastructure disclosure policies should be made mandatory to increase the transparency and replicability of the digital sustainability assessment. Individual countries often had missing or irregular data on power provisioning or physical capacity throughout our data. This irregularity makes it hard to do nationwide energy planning and comparative international studies. Regulators in particular high-growth markets ought to harmonise with international principles (e.g. ITU-T L.1300 or ISO 30134) that require standardised disclosures of energy, white space, and IT loads metrics.

Third, green public procurement (GPP) can be utilised to encourage investment in energy-efficient digital infrastructure. Governments, universities, and healthcare establishments typically rent or co-host servers in third-party buildings. Through conditional contracts based on energy transparency and minimal performance criteria, stakeholders in the public sector will be able to induce demand for green data centre services, mainly by providing services in underregulated areas.

Fourth, capacity-building investments and technical training should be made to ease the operational performance gap in energy-constrained economies. Effective cooling systems, air circulation, and server consolidation demand trained personnel and knowledge of ever-changing green IT strategies. International development agencies and cloud internet service providers may do their part to assist with training programs and mutual ventures that focus on infrastructural sustainability.

Lastly, the study proposes creating a Global Digital Infrastructure Sustainability Index (GDISI) that compounds white space and gross power indexes and normalised efficiency indexes across nations and regions. Such a tool would benchmark progress, dictate future study as the basis of climatic action, and increase global responsibility at an international level towards digital energy transitions.

Three clear implications emerge. First, regulators should establish mandatory energy and space metrics disclosure aligned with ISO 30134 and ITU-T L.1300 standards. Second, operators must prioritise modular, renewable-integrated designs and circular-energy practices like heat reuse. Third, researchers should refine the GDISI by integrating real-time utilisation and carbon-intensity data to enable transparent benchmarking of global digital sustainability progress.

ACKNOWLEDGMENT(S)

The authors would like to express their sincere appreciation to the dataset contributors from Kaggle and the open-access initiatives that provided the data used in this study. Additional thanks are extended to the academic supervisors and peer reviewers whose comments helped improve the quality and clarity of the research.

NOMENCLATURE

A_{ws}	available white space per region	[m^2]
A_{gp}	available gross power per region	[MW]
n	number of data centers	[-]
P_{avg}	average power per data center	[MW]
W_{avg}	average white space per data center	[m^2]

Greek letters

ρ	density of data centers per region	[-]
α	normalization factor for efficiency index	[-]

Subscripts and superscripts

int	internal capacity of white space/power
ext	external provisioned infrastructure

Abbreviations

CSV	Comma Separated Values
EDA	Exploratory Data Analysis
GDISI	Global Data Infrastructure Sustainability Index
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IT	Information Technology
MW	Megawatt
SDG	Sustainable Development Goal

REFERENCES

1. U. O. Matthew, J. S. Kazaure and N. U. Okafor, "Contemporary development in E-Learning education, cloud computing technology & internet of things," *EAI Endorsed Trans. Cloud Syst.,* Vol. 7, No. 20, p e3, 2021, https://doi.org/10.4108/eai.31-3-2021.169173.
2. Data Centres and Data Transmission Networks, IEA, https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks, [Accessed Oct. 26. 2025].
3. G. Anzolin and A. Lebdioui, "Three dimensions of green industrial policy in the context of climate change and sustainable development," *The European Journal of Development Research,* Vol. 33, No. 2, pp 371-405, 2021, https://doi.org/10.1057/s41287-021-00365-5.
4. J. Monstadt and K. Saltzman, How Data Centers Have Come to Matter: Governing the Spatial and Environmental Footprint of the 'Digital Gateway to Europe', *International Journal of Urban and Regional Research*, Vol. 49, No. 4, p 757-778, July 2025, https://doi.org/10.1111/1468-2427.13316.
5. P. Pang, Q. Chen, D. Zeng and M. Guo, Adaptive preference-aware co-location for improving resource utilization of power constrained datacenters," *IEEE Transactions on Parallel and Distributed Systems,* Vol. 32, No. 2, pp 441-456, 2020, https://doi.org/10.1109/TPDS.2020.3023997.
6. D. Nafus, E. M. Schooler and K. A. Burch, Carbon-responsive computing: Changing the nexus between energy and computing, *Energies,* Vol. 14, No. 21, p 6917, 2021, https://doi.org/10.3390/en14216917.
7. M. Kılıç, Evaluation of combined thermal–mechanical compression systems: A review for energy efficient sustainable cooling, *Sustainability,* Vol. 14, No. 21, p 13724, 2022, https://doi.org/10.3390/su142113724.

8. S. Long, Y. Li, J. Huang, Z. Li and Y. Li, A review of energy efficiency evaluation technologies in cloud data centers, *Energy and Buildings,* Vol. 260, p 111848, 2022, https://doi.org/10.1016/j.enbuild.2022.111848.
9. B. Martínez, S. Sánchez-Ruiz, M. Campos-Taberner, F. J. García-Haro and M. A. Gilabert, Exploring ecosystem functioning in spain with gross and net primary production time series, *Remote Sensing,* Vol. 14, No. 6, p 1310, 2022, https://doi.org/10.3390/rs14061310.
10. K. B. Ajide, R. O. Dauda and O. Y. Alimi, Electricity access, institutional infrastructure and health outcomes in Africa, *Environment, Development and Sustainability,* Vol. 25, No. 1, pp 198-227, 2023, https://doi.org/10.1007/s10668-021-02048-x.
11. I. Merrell, J. Phillipson, M. Gorton and P. Cowie, Enterprise hubs as a mechanism for local economic development in rural areas, *Journal of Rural Studies,* Vol. 93, pp 81-91, 2022, https://doi.org/10.1016/j.jrurstud.2022.05.016.
12. J. A. Jensen, D. Head and C. Mergy, Investigating sponsor decision-making: the role of schema theory, agency conflicts, and signaling theory in the persistence of naming rights agreements, *International Journal of Sports Marketing and Sponsorship,* Vol. 21, No. 3, pp 467-486, 2020, https://doi.org/10.1108/IJSMS-06-2019-0067.
13. F. Nasser and F. Abdelkaoui, Bridging the Digital–Environmental Nexus: An Empirical Panel Analysis of ICT, CO2 Emissions, and Growth in Developing Nations, *Journal of Digital Economy,* 2025, https://doi.org/10.1016/j.jdec.2025.06.004.
14. M. M. Spanner and J. Wein, Carbon risk real estate monitor: making decarbonisation in the real estate sector measurable, *Journal of European Real Estate Research,* Vol. 13, No. 3, pp 277-299, 2020, https://doi.org/10.1108/JERER-05-2020-0031.
15. N. Fose, A. R. Singh, S. Krishnamurthy, M. Ratshitanga and P. Moodley, Empowering distribution system operators: A review of distributed energy resource forecasting techniques, *Heliyon,* Vol. 10, No. 15, p e348002024, https://doi.org/10.2139/ssrn.4646481.
16. V V. N. Annapareddy, B. Preethish Nanan, V. B. Kommaragiri, A. L. Gadi and S. Kalisetty, Emerging Technologies in Smart Computing, Sustainable Energy, and Next-Generation Mobility: Enhancing Digital Infrastructure, Secure Networks, and Intelligent Manufacturing, SSRN, Dec. 15, 2022. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5204960, [Accessed Oct. 29. 2025].
17. S. Arnold-Keifer, S. Hirzel and C. Rohde, Understanding Energy Demand of the Tertiary Sector by Energy Carriers and End-Uses: An Integrated Bottom-Up and Top-Down Model Taking Germany as the Example, *Energies,* Vol. 17, No. 17, p 4486, 2024, https://doi.org/10.3390/en17174486.
18. M. J. Ibáñez, Social entrepreneurship review: A gap in the Latin American context, *Management Research: Journal of the Iberoamerican Academy of Management,* Vol. 20, No. 1, pp 6-24, 2022, https://doi.org/10.1108/MRJIAM-09-2021-1232.
19. D. D. Slate, A. Parisot, L. Min, P. Panciatici and P. Van Hentenryck, Adoption of Artificial Intelligence by Electric Utilities, *Energy LJ,* Vol. 45, No. 1, pp. 1–23, 2024, https://doi.org/10.2139/ssrn.4847872.
20. H.P. Das, Y.-W. Lin, U. Agwan, L. Spangher, A. Devonport, Y. Yang, J. Drgoňa, A. Chong, S. Schiavon and C.J. Spanos, Machine learning for smart and energy-efficient buildings, *Environmental Data Science,* Vol. 3, p e1, 2024, https://doi.org/10.1017/eds.2023.43.
21. T. Thein, M. M. Myo, S. Parvin and A. Gawanmeh, Reinforcement learning based methodology for energy-efficient resource allocation in cloud data centers, *Journal of King Saud University-Computer and Information Sciences,* Vol. 32, No. 10, pp 1127-1139, 2020, https://doi.org/10.1016/j.jksuci.2018.11.005.

22. P. E. Stek, Mapping high R&D city-regions worldwide: A patent heat map approach, *Quality & Quantity,* Vol. 54, No. 1, pp 279-296, 2020, https://doi.org/10.1007/s11135-019-00874-w.
23. T. Cai and Z. Hong, Exploring the structure of the digital economy through blockchain technology and mitigating adverse environmental effects with the aid of artificial neural networks, *Frontiers in Environmental Science,* Vol. 12, p 1315812, 2024, https://doi.org/10.3389/fenvs.2024.1315812.
24. B. N. Jørgensen and Z. G. Ma, Regulating AI in the Energy Sector: A Scoping Review of EU Laws, Challenges, and Global Perspectives, *Energies,* Vol. 18, No. 9, p 2359, 2025, https://doi.org/10.3390/en18092359.

Paper submitted: 02.07.2025
Paper revised: 13.10.2025
Paper accepted: 16.10.2025