# “An integrated approach to assessing data center efficiency: The Ukrainian context”


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# AN INTEGRATED APPROACH TO ASSESSING DATA CENTER EFFICIENCY: THE UKRAINIAN CONTEXT

## Abstract

This study aims to develop and test an integrated approach to assessing data center (DC) efficiency using multi-criteria analysis (MCA) and to substantiate priority areas of state policy for developing DC infrastructure in Ukraine. The methodological approach is based on reliability, energy efficiency, and market position criteria. Reliability is assessed using the Uptime Institute's international classification system, with logarithmic normalization of downtime on a fixed-point scale. Energy efficiency is measured by the Power Usage Effectiveness (PUE) metric. Market position is based on market share measured by financial revenue. The methodology was tested on a sample of 14 Ukrainian DCs. The findings demonstrate substantial variation in the efficiency levels of Ukrainian DCs, with integral scores ranging from 29.60 to 72.50 on a 100-point scale. Based on the proposed classification, two DCs were assigned to the high-efficiency group, one to the medium-efficiency group, and eleven to the basic-efficiency group. Reliability emerged as the dominant determinant of DC efficiency, exerting the strongest influence on final assessment outcomes, while energy efficiency provided an additional but significant contribution to overall performance differentiation. Sensitivity analysis confirmed the robustness and stability of the proposed framework under alternative weighting scenarios. The study identifies key challenges facing the Ukrainian DC sector and proposes a roadmap for 2026–2030 to improve reliability, energy efficiency, and compliance with international standards. The proposed approach can support evidence-based decision-making by public authorities, investors, and infrastructure planners when forming investment budgets and justifying decisions on infrastructure scaling and peripheral network deployment.

**Keywords** data centers, digital infrastructure, multi-criteria analysis, reliability, energy efficiency, Power Usage Effectiveness (PUE), public finance

**JEL Classification** O33, O38, H54, Q48, L86

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## INTRODUCTION

The rapid digital transformation of the economy and society is driving a growing need for reliable infrastructure solutions for storing and processing large volumes of data. International experience demonstrates that data centers (DCs) are becoming a cornerstone of the digital ecosystem and a critical factor in shaping a state's digital sovereignty. The spread of artificial intelligence technologies and the growing demand for scalable digital solutions make energy efficiency, cybersecurity, and compliance with international standards pressing issues, particularly in developing countries where energy systems are often constrained or overloaded.

In Ukraine, the reform of the public investment management system highlights the need to improve approaches to assessing the effectiveness of DCs as key infrastructure facilities. Ukrainian data centers face multiple challenges, including limited energy resources, regulatory constraints, and underdeveloped financial markets. Therefore, scaling DC services in Ukraine requires establishing clear efficiency assessment criteria based on international practices and adapted to national conditions.

Growing demand for computing power, particularly in the context of AI system development, creates new challenges for energy systems, regulatory models, and supply chains, while simultaneously opening opportunities for partnerships between government, business, and technology companies. Despite the significant attention paid to various technical aspects of DC operation, the scientific literature lacks consistent approaches to their comprehensive assessment. This complicates the formation of informed management decisions at both the state and regional levels and among potential service consumers and investors. In this context, applying the multi-criteria analysis (MCA) method allows for a comprehensive assessment of DC efficiency, considering multi-faceted factors to ensure the validity of management decisions.

Furthermore, it is essential not only to design an assessment tool but also to classify DCs by their primary purpose areas based on operational efficiency, in particular, the ability to ensure long-term operational stability and reliability under peak loads.

The purpose of this paper is to develop and test an integrated approach to assessing the effectiveness of data centers using multicriteria analysis (MCA) and to substantiate key areas of state policy for DC infrastructure development in Ukraine.

# 1. THEORETICAL BASIS

## 1.1. Existing approaches to data center efficiency assessment

In today's environment, data centers (DCs) are becoming a key infrastructure foundation for the development of the information society. At the beginning of March 2026, approximately 12,000 data centers were operating worldwide, with the largest number concentrated in the United States – 5,426. Accordingly, 529 data centers were operating in Germany, 523 in the United Kingdom, more than 449 in China, 332 in France, 144 in Australia, 99 in Singapore, and 43 in South Korea (Brightlio, 2026). Such differences in the number of data centers in individual countries are determined by the size of the economy, the level of scientific and technological potential, the digitalization of production and social processes, and the demand for cloud services and data, among others.

Significant attention is paid to building a broad network of data centers to support next-generation AI innovation and the ever-changing customer needs (McKinsey & Company, 2024; Prabhakar et al., 2026). DCs are becoming key elements of digital infrastructure and can act as flexible energy consumers in smart-grid systems (Takci et al., 2025). Future demand for DC capacity will depend on many factors, the impact of which is difficult to predict. These include: growing video and gaming streaming traffic; the development and active use of digital technologies and artificial intelligence; a rapidly growing blockchain-based IT infrastructure; the rapid growth of internet users; and the development of the Internet of Things (IoT) thanks to the implementation of M2M technologies (UNCTAD, 2024; Isazadeh et al., 2023; McKinsey & Company, 2025).

Data centers are commonly classified into the following functional types: hyperscale, colocation, and enterprise DCs, while AI servers are considered as a separate segment due to the growing demand (Kamiya & Coroamă, 2025). A study by the United Nations Environment Programme (UNEP, 2025) systematized the main models for organizing the operation of data centers and increasing their energy efficiency in developing countries.

Existing studies devote considerable attention to individual dimensions of data center performance, particularly reliability, security, energy efficiency, and sustainability.

One of the key areas of data center assessment is operational reliability. The reliability rating is determined using the international infrastructure reliability and fault tolerance classification system developed by the Uptime Institute. Reliability is characterized by a Tier indicator – a standard that shows how well a data center is protected from failures and can ensure reliable and continuous operation (The Green Grid, 2012).

Although licensing of data center activities is not mandatory in most countries, they must comply with industry security and reliability standards, including SOC 2 and ISO/IEC 27001, as well as data protection and cybersecurity requirements. In addition, most data centers undergo voluntary certification according to the Uptime Institute Tier Classification System (Uptime Institute, 2012).

Most EU countries use international standards to ensure compliance with security and performance requirements, including ISO/IEC 30134-2:2026, which defines key performance indicators for data centers (ISO, 2026), and EN 50600-2-1, one of the key European standards for the design and operation of data centers (CENELEC, 2021). Compliance with these standards is an important benchmark for the development of DC infrastructure in Ukraine in the context of harmonization with European requirements and integration into a single digital space.

Another important aspect is energy efficiency. A distinctive feature of data centers is their high level of energy consumption: they can consume up to 40 times more energy than traditional office buildings, and energy supply costs tend to increase (Shehabi et al., 2024).

The rapid growth of data centers and their energy needs poses challenges to the energy system (European Commission, 2025), and improving DC energy efficiency is becoming increasingly important and requires more active promotion of cost-effective energy efficiency measures across all sectors (European Parliament and Council of the European Union, 2023). In 2024, the annual electricity consumption of DCs worldwide was estimated at approximately 415–485 TWh, accounting for about 1.5% of global electricity consumption. Over the preceding five years, this indicator grew at an average rate of 12% per year, highlighting the accelerating impact of data center operations on global energy systems (IEA, 2024). However, the global real estate market is expected to see a 17–20% increase in data center supply by 2026 (JLL, 2026; Naumenkova et al., 2026).

Recent research indicates significant progress in the development of data center efficiency metrics. Traditional indicators such as Power Usage Effectiveness (PUE) and Data Center Infrastructure Efficiency (DCiE) remain widely used for evaluating energy performance. However, their application reveals both advantages and limitations (Long et al., 2022). With the increasing adoption of virtualization, containerization, and serverless computing, such limitations have become more pronounced, prompting the introduction of new indicators such as Server Power Usage Effectiveness (SPUE), which aim to capture energy use at a more granular level (Safari et al., 2025).

Current studies emphasize the need to complement these indicators with additional metrics that provide a more comprehensive representation of data center technical performance (Cockcroft, 2025; Khosravi et al., 2024). This is particularly relevant for cooling systems, which have a substantial impact on both energy efficiency and operating costs (Haghshenas et al., 2023; Ranran et al., 2023; Cho & Lim, 2023; Abdilla et al., 2025).

The environmental indicators of DC operations are becoming crucial. Assessing the impact of DCs on energy systems and sustainable development is a priority area of national and international research (IEA, 2022; Mishchenko et al., 2025). To evaluate the data center operation in the context of sustainable development, performance indicators such as CUE (Carbon Usage Effectiveness) and WUE (Water Usage Effectiveness) are used. In particular, CUE measures the total carbon emissions associated with data center operation relative to the energy consumed by IT equipment, while WUE characterizes the efficiency of water resource utilization by the data center.

At the same time, broader methodological reviews emphasize the need for multiscale and sustainabilityoriented metrics (Shao et al., 2022). The values of these indicators are significantly influenced by climatic conditions, technological solutions, and data center architectures (Lei & Masanet, 2022; Depoorter et al., 2015), which is of critical importance for strategic infrastruc-


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ture planning (Hussein et al., 2023). Examples of effective public policy in digital infrastructure development illustrate the possibility of combining the optimization of computing resource allocation with the achievement of environmental goals (Wang et al., 2025; Zhu et al., 2026; Güğül et al., 2023).

Multi-criteria approaches are widely used in management decision-making across various industries, although the choice of a specific method may significantly influence evaluation outcomes (Pujadas et al., 2017; Zlaugotne et al., 2020; Naumenkova et al., 2020). Such approaches enable the consideration of multidimensional criteria and support more informed decision-making processes. The literature emphasizes the importance of integrating environmental, social, and economic criteria within comprehensive assessment frameworks (Pardo-Bosch & Aguado, 2016; Naumenkova et al., 2024).

Multi-criteria assessment methods have increasingly been employed in DC sustainability studies and related infrastructure research. Approaches based on AHP, ANP, TOPSIS, fuzzy TOPSIS, and GIS-supported decision models enable the integration of multiple technical, environmental, economic, and operational criteria within a unified analytical framework (Zhang & Yang, 2021; Wang et al., 2022; Zubiria et al., 2022; Mathebula & Mbuli, 2025). These studies demonstrate the methodological potential of MCA for evaluating complex infrastructure systems. However, many existing applications rely on relatively sophisticated weighting and decision-support procedures, creating a need for more transparent and practically applicable approaches to data center efficiency assessment, particularly in data-constrained environments.

An important aspect of DC management is improving the data collection and exchange system,

**Table 1.** Key dimensions and indicators of data center performance assessment

| Indicator | Definition | Measurement unit / scale | Application |
|---|---|---|---|
| **1. Security & Reliability** | | | |
| Security compliance | Compliance with ISO/IEC 27001, SOC 2, GDPR/NIS2 | Certification status | Ensures trust and regulatory alignment |
| Reliability (Tier) | Guaranteed uptime according to Uptime Institute classification | Tier I-IV | Differentiates critical vs. standard DCs |
| Availability (SLA) | Guaranteed service uptime in contracts | % (e.g., ≥ 99.98%) | Benchmark for critical workloads |
| Network latency | Average response time of data center systems | ms | Critical for cloud and AI platforms |
| **2. Energy and Resource Efficiency** | | | |
| Energy efficiency (PUE/DCiE) | PUE = Total facility energy / IT energy; DCiE = IT energy / Total facility energy | Numeric value ≥ 1.0 | Core metric of operational efficiency |
| Cooling efficiency | Ratio of cooling energy to total energy | % | Optimization of HVAC systems |
| Carbon usage effectiveness (CUE) | $CO_2$ emissions per unit of IT energy | kg $CO_2$/kWh | Environmental sustainability assessment |
| Water usage effectiveness c (WUE) | Water consumption per unit of IT energy | L/kWh | Environmental sustainability assessment |
| Renewable energy share | Share of renewable energy in total consumption | % | Indicator of green transition |
| CPU/RAM/Storage utilization | Ratio of used computing resources to available capacity | % utilization | Internal efficiency of IT workloads |
| **3. Infrastructure Capacity and Market Position** | | | |
| Space utilization | Ratio of occupied rack/room space to total available | % utilization | Optimization of physical infrastructure |
| Scalability index | Ability to expand resources without performance loss | Qualitative/quantitative score | Strategic planning for growth |
| Operation cost per rack | Average cost of maintaining one rack space | USD per rack/year | Investment and budgeting decisions |
| Market position | Relative share of services/ financial revenue in the market | % | Strategic competitiveness indicator |

especially in segments where these data are limited or inaccessible (e.g., small data centers). The complexity of data collection tasks for calculating key performance indicators remains relevant (Kuzay et al., 2026), necessitating the development of new approaches to modeling and forecasting DC development at the national level.

Despite significant progress in the assessment of data center energy efficiency, reliability, and sustainability, the existing literature lacks integrated evaluation frameworks tailored to the needs of public authorities and investors, particularly in environments characterized by limited data availability. Most existing approaches either focus on individual technical dimensions or rely heavily on expert-based weighting procedures. Consequently, there is a need for a multi-criteria assessment approach to data center efficiency that combines methodological transparency, practical applicability, and the capacity to support decisionmaking in countries facing elevated infrastructure risks and underdeveloped financial markets, such as Ukraine.

The reviewed literature suggests that reliability and energy efficiency remain the most widely recognized technical dimensions of data center performance, while market-related indicators reflect the practical competitiveness and demand for data center services. The integration of these dimensions into a unified assessment framework provides an opportunity to combine engineering, operational, and economic perspectives within a single evaluation model.

Thus, the generalization of indicators for data center performance assessment allows to identify several key dimensions of evaluation (Table 1).

These indicators represent the most widely used approaches to assessing data center performance in both academic research and professional practice. Their applicability depends on the objectives of the assessment, data availability, and the specific characteristics of data center operation. Reliability, energy and resource efficiency, and market-related indicators emerge as the principal dimensions of data center performance evaluation. Together, these dimensions provide the conceptual foundation for the integrated multi-criteria assessment approach developed in the following section.

## 1.2. Formation of the integrated approach to data center efficiency assessment

The literature review suggests that reliability and energy efficiency are among the most widely recognized technical dimensions of data center performance assessment. In addition, market-related indicators reflecting competitiveness and demand for data center services may serve as a complementary economic dimension of evaluation. Integrating these dimensions within a unified multi-criteria analysis (MCA) framework enables the combination of engineering, operational, and economic perspectives into a comprehensive assessment model.

Reliability is a fundamental requirement for the operation of a data center as a critical infrastructure facility, as even short-term downtime can lead to system failures under heightened operational, energy, and cyber risks. This is why the reliability criterion carries the greatest weight in the comprehensive assessment, which is consistent with the risk-first infrastructure assessment principle.

Energy efficiency is a secondary priority as it directly impacts long-term operational sustainability and cost structure.

Market share is measured using revenue-based market share within the analyzed sample and is incorporated as an auxiliary criterion with limited weight to prevent commercial scale from dominating technical performance characteristics.

In the proposed model, the relative importance of criteria is established through the maximum values of the rating scale (*SRmax, SEmax,* and *SMmax*), which avoids the introduction of additional weighting factors, ensures a clear interpretation of the results, and is more convenient for applied analysis and the formation of management decisions. In the baseline scenario, the reliability criterion is set at an upper limit ($SR_{max}$) of 50 points and a lower limit ($SR_{min}$) of 10 points, since even the minimum Tier level characterizes basic operability. The value set for the energy efficiency criteria ($SE_{max}$) is 40 points, for the market position ($SM_{max}$) is 10 points, and the lower limit for them is not set separately, since it, naturally, equals zero in the absence of corresponding advantages.



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Calculating the score for reliability (SR). Reliability is assessed using the Uptime Institute's international classification system. The Tier standard has four levels based on guaranteed uptime (Table 2).

For quantitative interpretation, logarithmic normalization of downtime with fixed score limits was used.

$$SR = SR_{\min} + \left(SR_{\max} - SR_{\min}\right) \cdot \frac{\left(\log_{10}\left(T_{\max}\right) - \log_{10}\left(T_i\right)\right)}{\left(\log_{10}\left(T_{\max}\right) - \log_{10}\left(T_{\min}\right)\right)}, \quad (1)$$

where $SR$ – reliability points; $T_i$ – actual downtime of the corresponding Tier (hours); $T_{max}$ – maximum downtime (Tier I); $T_{min}$ – minimal downtime (Tier IV); $SR_{max}$ = 50, $SR_{min}$ =10.

This approach has certain advantages, namely:

- it reflects real business risk: even a small reduction in downtime (from hours to minutes) makes a huge difference for critical systems;
- helps avoid skews: SLA percentages are very close (99.982% vs 99.995%), but the logarithm of downtime shows that the difference between 1.6 hours and 26 minutes is significant; and
- provides flexibility in maintaining the desired range between the minimum and maximum value in points.

The lower limit of 10 points is set because the data centers being analyzed are functioning infrastructure facilities, and therefore even the minimum Tier level characterizes operational suitability.

In the absence of an official Tier-level certificate, the assessment is carried out using lower-level parameters. This conservative approach is based on the principle of using verified data and aims to increase the reliability of results and encourage official certification.

Calculating the score for energy efficiency (SE). Energy efficiency is assessed based on the power usage effectiveness (PUE) indicator, which characterizes the ratio of the total amount of DC energy consumed (for cooling systems: air conditioners, liquid cooling; uninterruptible power supplies (UPS); lighting, security systems, infrastructure costs) and energy used only by IT equipment: servers, storage systems, and network equipment. The minimum possible PUE value is 1.0 (energy is consumed only by IT equipment), in which case the DC's energy efficiency is maximized. In practice, PUE values for DCs range from 1.1 to 2.0.

Normalization is performed relative to a physically achievable reference value:

$$SE = \frac{PUE_{et}}{PUE_i} \cdot SE_{\max}, \quad (2)$$

where $SE$ – energy efficiency scores; $PUE_{et}$ =1.0 – reference value; $PUE_i$ – actual average value of the indicator; $SE_{max}$ = 40.

The $SE$ value cannot exceed the established upper limit $SE_{max}$. This approach reflects the indicator's engineering nature and ensures a proportional assessment relative to the theoretically optimal level.

Calculating the score for market position (SM). Market position is assessed based on market share

**Table 2.** Comparison of data center reliability levels (Tiers) by SLA

Source: Uptime Institute (2012).

| Tier Level | Characteristic | SLA value, % | Maximum downtime during the year |
|---|---|---|---|
| Tier I | Basic level: minimal infrastructure, no redundancy, possible downtime | 99.671 | ≈ 28.8 hours |
| Tier II | Partial redundancy of power and cooling systems (N+1) | 99.741 | ≈ 22 hours |
| Tier III | Full redundancy of all systems (N+1), fault tolerance, and the ability to serve clients without interrupting operations | 99.982 | ≈ 1.6 hours |
| Tier IV | Highest level: maximum redundancy (2N+1), dual power supply, full fault tolerance, minimal downtime risks, even in the event of serious accidents | 99.995 | ≈ 26 minutes |

measured by financial revenue within the analyzed sample:

$$SM = \frac{M_i}{M_{\max}} \cdot SM_{\max}, \qquad (3)$$

where $M_i$ – annual financial revenue of the $i$-th DC; $M_{max}$ – the highest annual financial revenue recorded among the DCs included in the sample. $SE_{max}$ = 10.

Annual financial revenue for 2025 was used as the basis for calculating market position scores. Therefore, the indicator reflects each data center's share of total revenue within the analyzed sample rather than within the entire Ukrainian data center market. Revenue-based market share was selected because it provides a comprehensive measure of the economic scale of data center operations and the market demand for their services.

Although the main emphasis is on technical assessment criteria (reliability and energy efficiency), the use of this criterion can be useful in strategic analysis for investors, government agencies or business partners. It should be noted, however, that market share is not always related to quality or reliability, as large DCs may gain significant market share more due to marketing than technical characteristics.

Calculating the integral efficiency indicator (I). Given the established threshold values, the integral indicator for assessing DCs looks like this:

$$I = SR + SE + SM, \qquad (4)$$

where $SR$ – reliability scores; $SE$ – energy efficiency scores; $SM$ – market share scores.

The maximum value of the integral assessment is 100 points.

The proposed methodological approach combines logarithmic normalization of technical risk, engineering interpretation of energy efficiency, and a market indicator of competitive position, providing a comprehensive assessment, with priority given to technical characteristics.

## 2. RESULTS AND DISCUSSION

DCs in Ukraine operate as commercial enterprises that are regulated by general norms and rules regarding telecommunications services, energy supply, security, and information protection. The legal basis for data centers' activities is the Law of Ukraine "On Cloud Services", which defines a data center as a specialized technical complex that includes engineering, information, communication, software, and hardware infrastructure (Verkhovna Rada of Ukraine, 2022). The National Commission for the State Regulation of Electronic Communications, Radio Frequency Spectrum, and the Provision of Postal Services regulates the cloud services market. The State Service of Special Communications and Information Protection of Ukraine may participate in regulating information security issues related to cloud communications. The Ministry of Digital Transformation of Ukraine is the central executive body responsible for the formation and implementation of state policy in the field of cloud services.

In 2026, 58 data centers were operating in Ukraine, providing hosting, colocation, and cloud computing services (Brightlio, 2026). The main market players are represented by large DCs that have their own, mostly certified, sites and serve the public sector and large corporations, as well as centers focused on medium-sized business clients (Stack Systems, 2021). There are also corporate data centers, information about which is not included in public statistics. Due to limited access to information and the fact that most DCs serve the internal needs of individual companies, the sample was compiled from 14 commercial DCs.

To assess data centers' energy consumption, approaches to summarizing energy consumption information are of particular importance given the limited availability of official statistics. A comparative analysis of the main approaches – "bottom-up", "top-down", and "temporal proxy extrapolation" (Kamiya & Coroamă, 2025; Kamiya & Bertoldi, 2024) – allows us to specify the possibility of their practical application for the analysis of the Ukrainian DC segment.

The bottom-up approach is most relevant for Ukraine, as it allows for the actual technical char-



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acteristics of equipment (servers, cooling systems, and networking equipment) to be taken into account and combined with data on the actual installed base. This ensures more accurate estimates, even in the face of limited official reporting.

The top-down approach is based on aggregated government and corporate data, but the fragmentation and irregularity of available information complicate its application in Ukraine.

Temporal proxy extrapolation can be useful for forecasting, but the risk of overestimating results is high in conditions of market volatility and rapid changes in the digital infrastructure.

Therefore, for the Ukrainian DC segment, it makes sense to use a bottom-up approach as a baseline, supplemented by individual elements of a top-down approach. This allows for a more balanced assessment of data center energy consumption, accounting for key performance indicators and public policy needs for digital infrastructure development.

Based on the proposed methodology, information was summarized, and the performance of 14 data centers was assessed according to three criteria: reliability, energy efficiency, and market position (Table 3).

All calculations and assessment results are based on data for 2025, including reliability, energy-efficiency, and market-position indicators. The results indicate significant differentiation in the integrated scores between data centers. Specifically, moving from Tier II to Tier III is accompanied by a disproportionate increase in the integrated score, confirming the nonlinear impact of reliability on overall performance. This is illustrated by the example of DC3, where a reduction in Tier level leads to a significant reduction in the final score.

Data centers with low integral index values (29–35 points) are characterized by a combination of three factors: lack of confirmed Tier certification, relatively high PUE values, and a small market share. In particular, for DC6 and DC7, the presence of the Tier III* designation without official confirmation leads to a reduction in points for the reliability criterion.

The results in Table 3 show that most Ukrainian DCs provide a basic or average level of reliability,

**Table 3.** Efficiency assessment of Ukrainian data centers in 2025

| DC number in the sample | Reliability | | Energy efficiency | | Market position | | Efficiency level depending on the value of the integral indicator (*I*), scores | | |
|---|---|---|---|---|---|---|---|---|---|
| | $Tier_i$ | SR, points | PUE | SE, points | ΔM, % | SM, points | high ($I \geq 70$) | medium ($40 \leq I < 70$) | basic ($I < 40$) |
| 1 | III | 37.50 | 1.6 | 25.00 | 30 | 10 | 72.50 | | |
| 2 | III | 37.50 | 1.5 | 26.67 | 22 | 7.3 | 71.50 | | |
| 3 | II | 12.56 | 1.7 | 23.53 | 15 | 5.0 | | 41.09 | |
| 4 | II | 12.56 | 1.9 | 21.05 | 4 | 1.3 | | | 34.95 |
| 5 | n/a | 10.00 | 1.8 | 22.22 | 4 | 1.3 | | | 33.56 |
| 6 | III* | 12.56 | 1.9 | 21.05 | 3 | 1 | | | 34.62 |
| 7 | III* | 12.56 | 1.9 | 21.05 | 3 | 1 | | | 34.62 |
| 8 | n/a | 10.00 | 2.0 | 20,00 | 2 | 0.7 | | | 30.67 |
| 9 | II | 12.56 | 2.0 | 20.00 | 3 | 1 | | | 33.56 |
| 10 | II | 12.56 | 2.0 | 20.00 | 3 | 1 | | | 33.56 |
| 11 | I-II* | 10.00 | 2.15 | 18.60 | 3 | 1 | | | 29.60 |
| 12 | II | 12.56 | 2.0 | 20.00 | 3 | 1 | | | 33.56 |
| 13 | n/a | 10.00 | 2.15 | 18.60 | 3 | 1 | | | 29.60 |
| 14 | II* | 10.00 | 2.02 | 20.00 | 2 | 0.7 | | | 30.67 |

*Note:* * means without official confirmation.

Cell shading indicates DC efficiency groups:
high-efficiency (I ≥ 70);
medium-efficiency (40 ≤ I < 70);
basic-efficiency (I < 40).

which corresponds to the ability to operate continuously with limited annual downtime.

The energy efficiency of Ukrainian DCs, for which PUE values are in the range of 1.4–2.0, is in line with the global average, but inferior to the indicators of leading global providers. Thus, the PUE for the Amazon Web Services (AWS) data center is 1.15, for Google Cloud Platform it is 1.10–1.12, and for the Facebook (Meta) Forest City Data Center it is 1.10 (IEA, 2021; Microsoft Datacenters, 2024). Thus, the energy efficiency of domestic DCs can be significantly improved by implementing modern energy management technologies and infrastructure optimization, as provided for in the requirements and provisions for harmonization with the Energy Efficiency Directive (European Parliament and Council of the European Union, 2023).

To test the robustness of the results, a sensitivity analysis was conducted by changing the maximum values of the estimates in accordance with the criteria ($SR_{max}$ and $SE_{max}$) that determine their relative importance in the model. In the analysis, variation was applied only to technical criteria (reliability and energy efficiency), while the maximum value of market position scores ($SM_{max}$) was left unchanged, given its auxiliary nature and limited impact on a DC's technical efficiency (Table 4).

Sensitivity analysis shows that varying the maximum score values for technical criteria leads to a proportional change in the integral scores but does not affect the overall ranking of data centers. In particular, increasing the upper limit of the reliability criterion ($SR_{max}$) is accompanied by an increase in the integral scores by +10–20 points, while increasing the limit of the energy efficiency criterion ($SE_{max}$) provides a more moderate increase (+4–5 points), which mainly affects data centers with average performance values. Increasing the priority of the reliability criterion results in some data centers moving from the basic to the medium performance group. This is because the increased importance of Tier-related metrics strengthens the position of data centers with a higher Tier standard of architectural reliability.

The results confirm the model's robustness to changes in scale parameters and indicate that the

**Table 4.** Sensitivity analysis for alternative estimation ranges

| DC number | Baseline scenario ($SR_{max}$ = 50, $SE_{max}$ = 40, $SM_{max}$ = 10) | Reliability-prioritized scenario ($SR_{max}$ = 60, $SE_{max}$ = 30, $SM_{max}$ = 10) | | Energy-efficiency-prioritized scenario: ($SR_{max}$ = 40, $SE_{max}$ = 50, $SM_{max}$ = 10) | |
|---|---|---|---|---|---|
| | (*I*) | (*I*1) | Δ vs baseline (absolute change in score) | (*I*2) | Δ vs baseline (absolute change in score) |
| 1 | 72.50 | 91.87 | 19.37 | 71.87 | –0.62 |
| 2 | 71.50 | 91.67 | 20.17 | 71.26 | –0.24 |
| 3 | 41.09 | 53.50 | 12.41 | 46.33 | 5.24 |
| 4 | 34.95 | 46.12 | 11.17 | 39.57 | 4.62 |
| 5 | 33.56 | 44.67 | 11.11 | 39.11 | 5.56 |
| 6 | 34.62 | 45,78 | 11.17 | 39.24 | 4.62 |
| 7 | 34.62 | 45,78 | 11.17 | 39.24 | 4.62 |
| 8 | 30.67 | 40.70 | 10.03 | 35.70 | 5.03 |
| 9 | 33.56 | 44.20 | 10.64 | 37.92 | 4.36 |
| 10 | 33.56 | 44.20 | 10.64 | 37.92 | 4.36 |
| 11 | 29.60 | 38.91 | 9.30 | 34.26 | 4.65 |
| 12 | 33.56 | 44.20 | 10.64 | 37.92 | 4.36 |
| 13 | 29.60 | 38.91 | 9.30 | 34.26 | 4.65 |
| 14 | 30.67 | 40.70 | 10.03 | 33.96 | 3.29 |

Cell shading indicates DC efficiency groups:
high-efficiency (I ≥ 70);
medium-efficiency (40 ≤ I < 70);
basic-efficiency (I < 40).



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relative positions of the assessment objects are maintained across different scenarios. Thus, the use of a scenario approach within the proposed methodology ensures its flexibility and adaptability to changing management priorities (risk-first vs energy-first).

First, the key differentiating factor is the Tier certification level. The lack of official proof significantly lowers the overall assessment, even if the technical infrastructure meets the required level. This underscores the importance of increasing market transparency and standardization. Second, energy efficiency measures indicate significant potential for optimization. Compared to global leaders, Ukrainian DCs exhibit higher PUE values, leading to higher operating costs and reduced competitiveness. Third, the limited market share of most operators indicates industry fragmentation and uneven distribution of the customer base.

Thus, the identified problems directly reflect the assessment results: low SR values are due to a lack of certification, while SE values indicate a lag in improving energy efficiency. Next, based on the comprehensive assessments, data centers were grouped by efficiency into three groups: high, medium, and basic efficiency (Table 5).

The division of data centers into groups is determined by several factors. For missioncritical systems such as AI platforms, government services, banking, and ecommerce, it is necessary to select data center services certified at a level not lower than Tier III, with implemented disaster recovery services in EU countries and support for GPU cluster solutions for AI/ML and SAP HANA. Large corporations and financial companies can rely on data centers certified according to ISO standards, compliant with GDPR/NIS2 requirements, and offering the highest guaranteed uptime (SLA ≥ 99.98%). For SMBs and ecommerce, the focus should be on services that provide flexible packages, high scalability, and reliable operation under peak loads.

ISO/IEC 27001 certification is a key differentiator between high-performance and basic data centers. For companies working with international clients, the data center provider must have international partnerships, which is a prerequisite for ensuring reliable data backup and recovery.

In the context of growing energy problems in Ukraine and limited access to energy supply, it is advisable to scale up DC services based on solutions aimed at increasing energy efficiency, the effectiveness of which is confirmed by international practice (Table 6).

First, the implementation of these solutions becomes relevant for DCs classified into medium and basic efficiency groups, focused on providing services to SMB and corporate clients. In the future, revenue from domestic DCs is expected to increase due to rising demand for cloud services and colocation. In addition, Ukrainian data centers are integrating with European partners, allowing clients to access international solutions and enhance their cybersecurity.

Another important issue for effective DC operation is overcoming personnel shortage, as by 2030, Ukraine is projected to need 10,000–15,000 new specialists in this field. Key areas of specialist training include DevOps and system administrators for multi-cloud, energy efficiency and cooling engineers, cybersecurity specialists, and AI engineers and data scientists for GPU clusters. Due to the high demand for specialists to work in DCs, Ukraine will face staff retention due to competition from the European market.

**Table 5.** Distribution of data centers by efficiency groups

| Group | Primary use area | Key features |
|---|---|---|
| High | Financial sector, government registries, critical infrastructure | Tier III–IV; SLA ≥ 99.98%; full reservation (2N/N+1); mandatory certification ISO/IEC 27001; high fault tolerance; support for DR services; focus on critical loads |
| Medium | E-commerce, SaaS, corporate systems | Tier II–III; SLA ~ 99.9–99.98%; partial reservation; availability or implementation of information security standards (in particular, ISO/IEC 27001); integration with European providers; scaling support; usage of GPU/AI solutions |
| Basic | SMB, backup storage, basic IT services | Tier I–II or without certification; SLA < 99.9%; limited reservation; basic hosting and colocation services; flexible business packages, affordable rates |

**Table 6.** Key solutions for improving energy efficiency when scaling data center services

Source: Compiled based on the United Nations Environment Programme (2025).

| Name | Description | Impact on energy consumption | Key benefits |
|---|---|---|---|
| Retail Colocation | Building a common infrastructure with payment for actual electricity use (pay-as-you-go) | PUE reduction to ~1.2–1.4 thanks to shared cooling system and load management | Reducing costs and increasing energy efficiency for SMB and startups |
| Wholesale Colocation | Lease of space and capacity for hosting your own equipment in a provider's DC | Achieving PUE value of ~1.6–1.8 depending on optimization | Scalability and control for large enterprises |
| Cloud services (IaaS, PaaS, SaaS) | Providing infrastructure, platforms or software as a service | Maintaining PUE ~1.1–1.2 at leading providers, improving energy efficiency on the backend by up to 20% | Reducing capital and operating costs through IT outsourcing |
| Hybrid/cloud models | Combining local and cloud systems | Reduced energy consumption by 10–15% compared to on-premises systems | Maintaining a flexible balance between control and scalability |
| Immersion Cooling Services | Using immersion cooling technologies offered by third-party suppliers | Reduced cooling energy consumption by up to 90% compared to air-cooled systems | Significant reduction in electricity costs |

Based on the analysis, key problems in the operation of DCs in Ukraine were identified: high energy dependence and limited energy efficiency; insufficient level of certification and cybersecurity; lack of systematic statistical reporting; low level of harmonization with European standards; and personnel shortage in the industry. Furthermore, the sector's development is constrained by its dependence on international cloud platforms such as Microsoft Azure and Amazon Web Services.

The results of data center efficiency assessment have outlined existing problems and made it possible to define a sequence of public policy measures aimed at enhancing the reliability and energy efficiency of data centers. These measures include regulatory adjustments, the development of energyefficient technologies, integration with the European digital market, infrastructure support for artificial intelligence, and workforce development (Table 7).

**Table 7.** State policy directions for the development of data centers

| No. | Direction | Key measures | Results-oriented |
|---|---|---|---|
| 1. | Regulatory framework | Data Center Law; harmonization with GDPR, NIS2, ISO/IEC, Tier, and PCI DSS; tax incentives; simplification of customs procedures | Formation of a transparent regulatory framework, integration with the EU, and increasing the investment attractiveness of DC center creation projects |
| 2. | Cloud services integration | Transition to IaaS/PaaS, multicloud; development of managed services | Expanding the range of services, becoming competitive in the global market |
| 3. | Infrastructure for AI | GPU clustering, HPC solutions; load optimization between local and European clouds | Supporting AI applications, attracting high-tech customers |
| 4. | Energy efficiency and green technologies | Liquid cooling; optimization PUE < 1.4; transition to renewable energy; location of DCs near sources of clean energy | Increasing environmental friendliness, saving costs, compliance with European requirements |
| 5. | Environmental KPI (ISO/IEC 30134) | Calculation WUE and CUE; implementation of monitoring and reporting systems | Ensuring transparency of environmental indicators, compliance with international standards |
| 6. | Energy security and cybersecurity | Modular DCs; backup sources; DR services; compliance with ISO/IEC 27001, GDPR/NIS2, PCI DSS, Tier | Increased reliability, data protection, compliance with EU requirements |
| 7. | Investments and financing | Raising capital for AI, cloud, energy efficiency, security, and backup solutions | Infrastructure modernization, sustainable financing |
| 8. | Staffing | Training DevOps, energy efficiency engineers, cyber specialists, AI engineers; retention programs | Reducing the outflow of personnel, forming a highly qualified workforce |
| 9. | Collection of statistical information | State register of DCs; mandatory KPI reporting; cooperation with the State Statistics Service; data anonymization | Ensuring the reliability of statistical data, increasing market transparency and predictability for investors |
| 10. | Integration with the European market | Partnerships with EU operators; joint SLA; geo-reservation; compliance with international standards | Deepening cooperation with the EU, entering the international market |


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**Table 8.** Action plan for the roadmap for developing DCs in Ukraine for 2026–2030

| Stages/Year | Basic actions |
|---|---|
| 2026–2027 | Implementation of mandatory certification of data centers according to Tier III–IV and ISO/IEC 27001 standards<br>Formation of a tax incentive system for green data centers<br>Commencement of regular government cybersecurity audits |
| 2027–2028 | Mass implementation of energy-efficient cooling and heat recovery technologies<br>Creation and development of state cyber incident response centers<br>Expanding the cloud services market for business and the public sector<br>Expansion and deepening of joint projects with European companies |
| 2028 | Integration of Ukraine into the European cloud services market<br>Attracting international investment for the construction of new DCs<br>Implementation of a system for monitoring and optimizing energy consumption in DCs<br>Development of digital infrastructure clusters (consolidation of DCs, telecom operators, innovative companies, and universities) |
| 2029 | Harmonization of Ukraine's national legislation in the field of digital infrastructure, cyber defense, and energy with EU directives<br>Extensive use of renewable energy sources in DCs<br>Increasing export volumes of Ukrainian cloud services<br>Expanding international cooperation in the field of cyber defense |
| 2030 | Ukraine becomes part of the single European digital market<br>Ensuring DC compliance with the highest international standards (Tier IV, ISO/IEC 27001, General Data Protection Regulation (GDPR), EU Directive 2023/1791 on energy efficiency (EED)<br>Formation of a developed competitive market for cloud services |

The implementation of the proposed public policy measures (Table 7) will contribute to the formation of a modern and competitive infrastructure of data centers, their integration into the European digital space, and increased energy efficiency and environmental friendliness, strengthening cybersecurity and reliability, attracting investment and qualified personnel, and creating a transparent statistical base for strategic planning of the industry.

In the context of energy instability, the development of data centers in Ukraine requires not only technical modernization but also strategic planning at the national and regional levels, which must take into account potential opportunities for access to electricity, investment support, regulatory flexibility, and integration into the overall economic development model.

To successfully implement key public policy measures in the field of digital infrastructure, cloud services, and cyber defense, a roadmap for developing Ukraine's DCs for 2026–2030 has been developed (Table 8).

Thus, by 2030, Ukrainian data centers will gradually transform from "server space" into service platforms integrated with the EU and optimized for AI and energy efficiency. Roadmap implementation will ensure Ukraine's gradual transition from the certification and implementation of energy-efficient technologies in 2026–2027 to integration into the European digital market in 2028–2030, creating the necessary preconditions for developing a digital infrastructure that meets the needs of the state, business, and society.

National data localization requirements may conflict with the global DC operating model. At the same time, their high energy consumption, which creates an additional burden on the power system, may not be consistent with the state's energy policy, and the dominance of global players in the digital market leads to unequal conditions for local companies.

## CONCLUSION

This study aims to develop and test an integrated multicriteria analysis (MCA) approach for assessing data center (DC) efficiency and to substantiate priority directions of state policy for DC infrastructure development in Ukraine.

The proposed MCA-based approach integrates three dimensions of data center performance: reliability, energy efficiency, and market position. Consistent with the “risk-first infrastructure assessment” principle, reliability was assigned the highest priority as the primary condition for operational continuity and infrastructure resilience.

The methodological approach was tested on a sample of 14 Ukrainian data centers. Integral efficiency scores on a 100-point scale ranged from 29.60 to 72.50. According to the proposed classification, two data centers were assigned to the high-efficiency group, one to the medium-efficiency group, and eleven to the basic-efficiency group. Reliability emerged as the principal factor differentiating data center performance and exerted the strongest influence on final efficiency scores, while energy efficiency measured by PUE provided an additional but significant contribution. Sensitivity analysis confirmed the robustness of the methodology under varying priorities, particularly in scenarios emphasizing either reliability or energy efficiency.

The study identified key challenges in the development of the Ukrainian data center sector and proposed priority policy directions to address them. A roadmap for 2026–2030 is proposed, outlining a sequence of public policy measures to increase data center reliability and energy efficiency and to ensure compliance with international standards in the context of modern digital infrastructure development.

The practical significance of the study lies in the possibility of using the proposed methodology by government agencies, investors, and data center operators when forming investment budgets and justifying decisions on scaling infrastructure and deploying peripheral networks. Limitations include the restricted sample size and data availability, particularly in segments of smaller data centers, which required conservative assumptions. Furthermore, environmental indicators such as WUE and CUE were not incorporated into the current framework due to data limitations, although their inclusion represents a promising direction for future research.

Future research should focus on expanding the dataset, refining efficiency metrics, incorporating environmental sustainability indicators, and further developing the MCA framework to enhance the accuracy, applicability, and policy relevance of data center efficiency assessment.

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## REFERENCES


1. Abdilla, A., Borg, S. P., & Licari, J. (2025). Relating measured PUE to the cooling strategy and operating conditions through a review of a number of Maltese data centres. *Energy Reports, 13,* 2612-2623. https://doi.org/10.1016/j.egyr.2025.02.013
2. Brightlio. (2026). *255 Data Center Stats* (March 2026). Brightlio Blog. Retrieved from https://brightlio.com/data-center-stats/
3. CENELEC. (2021). *EN 50600-2-1:2021. Data centre facilities and infrastructures – Building construction.* Brussels: European Committee for Electrotechnical Standardization. Retrieved from https://standards.iteh.ai/catalog/standards/clc/a9d359c5-b85a-4b92-a5e5-aebeb34f46d3/en-50600-2-1-2021
4. Cho, J., & Lim, S. (2023). Balanced comparative assessment of thermal performance and energy efficiency for three cooling solutions in data centers. *Energy, 285,* Article 129370. https://doi.org/10.1016/j.energy.2023.129370
5. Cockcroft, A. (2025, January 10). *Cloud PUE: Comparing AWS, Azure and GCP Global Regions.* The new Stack. Retrieved from https://thenewstack.io/cloud-pue-comparing-aws-azure-and-gcp-global-regions/
6. Depoorter, V., Oró, E., & Salom, J. (2015). The location as an energy efficiency and renewable energy supply measure for data centres in Europe. *Applied Energy, 140,* 338-349. https://doi.org/10.1016/j.apenergy.2014.11.067
7. European Commission (EC). (2025). *In focus: Data centres – an energy-hungry challenge.* European Commission. Directorate-General for Energy. Retrieved from https://energy.ec.europa.eu/news/focus-data-centres-energy-hungry-challenge-2025-11-17_en
8. European Parliament and Council of the European Union. (2023). *Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast)* Brussels: Council of the European Union. Retrieved from http://data.europa.eu/eli/dir/2023/1791/oj
9. Güğül, G. N., Gökçül, F., & Eicker, U. (2023). Sustainability analysis of zero energy consumption data centers with free cooling, waste heat reuse and renewable energy systems: A feasibility study. *Energy, 262*(Part B), Article 125495. https://doi.org/10.1016/j.energy.2022.125495
10. Haghshenas, K., Setz, B., Blosch, Y., & Aiello, M, (2023). Enough hot air: the role of immersion cooling. *Energy Inform, 6,* Article 14. https://doi.org/10.1186/s42162-023-00269-0
11. Hussein, Y. S., Alrashd, M., Alabed, A., & Zraiqat, A. (2023). Data centre infrastructure: Power efficiency and protection. In *Latest Advances and New Visions of Ontology in Information Science*. InTechOpen. https://doi.org/10.5772/intechopen.110014
12. IEA. (2021). *Data centre electricity consumption by region, Base Case, 2020–2030.* Retrieved from https://www.iea.org/data-and-statistics/charts/data-centre-electricity-consumption-by-region-base-case-2020-2030
13. IEA. (2022). *Data Centres and Data Transmission Networks.* Retrieved from https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks
14. IEA. (2024). *Energy demand from AI.* Retrieved from https://www.iea.org/reports/energy-and-ai/energy-demand-from-ai
15. Isazadeh, A., Ziviani, D., & Claridge, D. (2023). Global trends, performance metrics, and energy reduction measures in datacom facilities. *Renewable and Sustainable Energy Reviews, 174.* https://doi.org/10.1016/j.rser.2023.113149
16. ISO. (2026). *ISO/IEC 30134-2:2026 Information technology – Data centres key performance indicators. Part 2: Power usage effectiveness (PUE).* Retrieved from https://assets.vde-verlag.de/iec-normen/preview-pdf/info_isoiec30134-2%7Bed2.0%7Den.pdf
17. JLL. (2026). *Global Real Estate Outlook: Six Forces Reshaping Commercial Real Estate.* Retrieved from https://www.jll.com/en-us/insights/market-outlook/global-real-estate
18. Kamiya, G., & Bertoldi, P. (2024). *Energy consumption in data centres and broadband communication networks in the EU.* European Commission. https://doi.org/10.2760/706491
19. Kamiya, G., & Coroamă, V. C. (2025). *Data centre energy use: Critical review of models and results.* EDNA. Retrieved from https://www.iea-4e.org/wp-content/uploads/2025/05/Data-Centre-Energy-Use-Critical-Review-of-Models-and-Results.pdf
20. Khosravi, A., Sandoval, O., Taslimi, M., Sahrakorpi, T., Amorim, G., & Pabon, J. (2024). Review of energy efficiency and technological advancements in data center power systems. *Energy and Buildings, 323,* Article 114834. https://doi.org/10.1016/j.enbuild.2024.114834
21. Kuzay, M., Demirel, E., & Bayraktar, B., Vilestad, J., Kärnebro, A., Yilmaz, C., Melgaard, S. P., Juul, T., Nielsen, J. E., Fricker, R., Stoller, S., Humbert, G., & Koirala, B. P. (2026). A self-assessment framework for evaluating efficiency of data centers. *Energy Inform, 9,* Article 39. https://doi.org/10.1186/s42162-026-00652-7
22. Lei, N., & Masanet, E. (2022). Climate- and technology-specific PUE and WUE estimations for U.S. data centers using a hybrid statistical and thermodynamics-based approach. *Resources, Conservation and Recycling, 182,* Article 106323. https://doi.org/10.1016/j.resconrec.2022.106323
23. Long, I., Li, H., Huang, J., Li, Z., & Li, Y. (2022). A review of energy efficiency evaluation technologies

in cloud data centers. *Energy and Buildings, 260,* Article 111848. https://doi.org/10.1016/j.enbuild.2022.111848

24. Mathebula, J., & Mbuli, N. (2025). Application of TOPSIS for multi-criteria decision analysis (MCDA) in power systems: A systematic literature review. *Energies, 18*(13), Article 3478. https://doi.org/10.3390/en18133478
25. McKinsey & Company. (2024). *AI power: Expanding data center capacity to meet growing demand.* Retrieved from https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/ai-power-expanding-data-center-capacity-to-meet-growing-demand
26. McKinsey & Company. (2025). *The cost of compute: A $7 trillion race to scale data centers*. Retrieved from https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/the-cost-of-compute-a-7-trillion-dollar-race-to-scale-data-centers
27. Microsoft Datacenters. (2024). *Measuring datacenter energy and water use to improve Microsoft Cloud sustainability.* Retrieved from https://datacenters.microsoft.com/sustainability/efficiency/
28. Mishchenko, V., Naumenkova, S., Mishchenko, S., & Tishchenko, I. (2025). Formation and functioning of financial metaverse platforms. *Financial and Credit Activities: Problems of Theory and Practice*, *1*(60), 111-122. https://doi.org/10.55643/fcaptp.1.60.2025.4689
29. Naumenkova, S., Mishchenko, S., Mishchenko, V., & Tishchenko, I. (2026). Real estate investment trusts: Investment approaches and application prospects in the Ukrainian real estate market. *Investment Management and Financial Innovations, 23*(1), 374-394. http://dx.doi.org/10.21511/imfi.23(1).2026.28
30. Naumenkova, S., Tishchenko, I., Mishchenko, S., Mishchenko, V., & Ivanov, V. (2020). Assessment and mitigation of credit risks in project financing. *Banks and Bank Systems, 15*(1), 72-84. http://dx.doi.org/10.21511/bbs.15(1).2020.08
31. Naumenkova, S., Tishchenko, I., Mishchenko, V., & Mishchenko, S. (2024). Rethinking energy poverty alleviation through energy efficiency: Evidence from Ukraine. *Environmental Economics*, *15*(2), 198-214. http://dx.doi.org/10.21511/ee.15(2).2024.14
32. Pardo-Bosch, F., & Aguado, A. (2016). Sustainability as the key to prioritize investments in public infrastructures. *Environmental Impact Assessment Review, 60,* 40-51. https://doi.org/10.1016/j.eiar.2016.03.007
33. Prabhakar, K., Thomas, C., Merizzi, N., Kearns-Manolatos, D., & Parveen, I. (2026). *Deloitte's enterprise AI infrastructure survey: A 2028 outlook.* Retrieved from https://www.deloitte.com/us/en/insights/topics/technology-management/ai-infrastructure-survey.html
34. Pujadas, P., Pardo-Bosch, F., Aguado-Renter, A., & Aguado, A. (2017). MIVES multi-criteria approach for the evaluation, prioritization, and selection of public investment projects. A case study in the city of Barcelona. *Land Use Policy, 64,* 29-37. https://doi.org/10.1016/j.landusepol.2017.02.014
35. Ranran, M., Xuelian, B., Xin, X., & Ren, F. (2023). Energy performance evaluation in a data center with water-side free cooling. *Energy and Buildings, 295,* Article 113278. https://doi.org/10.1016/j.enbuild.2023.113278
36. Safari, A., Sorouri, H., Rahimi, A., & Oshnoei, A. (2025). A systematic review of energy efficiency metrics for optimizing cloud data center operations and management. *Electronics, 14*(11), Article 2214. https://doi.org/10.3390/electronics14112214
37. Shao, X., Zhang, Z., Song, P., Feng, Y., & Wang, X. (2022). A review of energy efficiency evaluation metrics for data centers. *Energy and Buildings, 271,* Article 112308. https://doi.org/10.1016/j.enbuild.2022.112308
38. Shehabi, A., Smith, S.J., Hubbard, A., Newkirk, A., Lei, N., Siddik, M.A.B., Holecek, B., Koomey, J., Masanet, E., & Sartor, D. (2024). *2024 United States data center energy usage report.* Berkeley, California: Lawrence Berkeley National Laboratory. Retrieved from https://escholarship.org/uc/item/32d6m0d1
39. Stack Systems. (2021). *Top-5 data-tsentriv Ukraiiny [Top 5 data centers in Ukraine].* (In Ukrainian). Retrieved from https://stack-systems.com.ua/blogs/top-5-data-centriv-ukrajiny
40. Takci, M., Qadrdan, M., Summers, J., & Gustafsson, J. (2025). Data centres as a source of flexibility for power systems. *Energy Reports, 13,* 3661-3671. https://doi.org/10.1016/j.egyr.2025.03.020
41. The Green Grid. (2012). *PUE: A Comprehensive Examination of the Metric* (White Paper No. 49). Retrieved from https://datacenters.lbl.gov/sites/default/files/WP49-PUE%20A%20Comprehensive%20Examination%20of%20the%20Metric_v6.pdf
42. UNCTAD. (2024). *Digital Economy Report 2024.* Retrieved from https://unctad.org/system/files/official-document/der2024_en.pdf
43. United Nations Environment Programme (UNEP). (2025). *Business models and finance to enhance energy efficiency in AI and data centres in emerging economies.* Retrieved from https://unepccc.org/wp-content/uploads/2025/10/business-models-and-finance-ai-data-centres-policy-brief.pdf
44. Uptime Institute. (2012). *Tier standard: Topology.* Retrieved from https://uptimeinstitute.com/publications/asset/tier-standard-topology
45. Verkhovna Rada of Ukraine. (2022). *Zakon Ukrayiny "Pro khmarni posluhy* [Law of Ukraine "On Cloud Services"]. (In Ukrainian). Retrieved from https://zakon.rada.gov.ua/laws/show/2075-20#Text
46. Wang, C., Zhao, Y., Zhang, Y., & Li, D. (2025). Environmental sustainability and firm performance: Unpacking the productivity effects of green data center pilots. *Journal of Environmental*

*Management, 395,* Article 127764. https://doi.org/10.1016/j.jenvman.2025.127764

47. Wang, Y., Tao, S., Chen, X., Huang, F., Xu, X., Liu, X., Liu, Y., & Liu, L. (2022). Method multi-criteria decision-making method for site selection analysis and evaluation of urban integrated energy stations based on geographic information system. *Renewable Energy, 194,* 273-292. https://doi.org/10.1016/j.renene.2022.05.087

48. Zhang, Q., & Yang, S. (2021). Evaluating the sustainability of big data centers using the analytic network process and fuzzy TOPSIS. *Environmental Science and Pollution Research, 28,* 17913-17927. https://doi.org/10.1007/s11356-020-11443-2

49. Zhu, Z., Imran Hunjra, A., Sami, M., & Zhao, S. (2026). From bytes to green: The impact of digital transformation on carbon performance. *International Review of Economics & Finance, 106,* Article 104999. https://doi.org/10.1016/j.iref.2026.104999

50. Zlaugotne, B., Zihare, L, Balode, L., Kalnbalkite, A., Khabdullin, A., & Blumberga, D. (2020). Multi-criteria decision analysis methods comparison. *Environmental and Climate Technologies, 24*(1), 454-471. https://doi.org/10.2478/rtuect-2020-0028

51. Zubiria, A., Menéndez, A., Hans-Jürgen Grande, H.-J., Meneses, H., & Fernández, G. (2022). Multi-criteria decision-making problem for energy storage technology selection for different grid applications. *Energies, 15*(20), Article 7612. https://doi.org/10.3390/en15207612