UNTAR Universitas Tarumanagara
Jurnal Ekonomi e-JE
E-ISSN 2580-4901
P-ISSN 0854-9842

Enabling Practical Decision Making For Sustainable Green Data Center Planning

Muhamad Faris Naufal Austen[1*] and Athor Subroto[2]
[1,2]Magister of Management, Faculty of Economy and Business, Universitas Indonesia, Jakarta, Indonesia

Email Address:
muhamad.faris11@ui.ac.id, athor.subroto@ui.ac.id*
[*]Corresponding author

***Submitted** 06-06-2023* ***Reviewed** 19-06-2023* ***Revised** 21-06-2023* ***Accepted** 21-06-2023* ***Published** 10-07-2023*

Abstract: Data centers play a crucial role in storing and processing data in today's digital age, leading to a surge in demand for sustainable green data center planning. However, implementing practical measures to achieve sustainability remains a challenge for data center managers. This study aims to aid their informed decision-making in sustainable green data center planning. Previous research has identified seven green data center key components: ICT governance, infrastructure, energy, equipment lifecycle, green technology, benchmarking, and business continuity. Subsequently, the study expanded by utilizing the FAHP method to evaluate the perspectives of various experienced data center. Those green data center components were evaluated against each other regarding the three sustainability criteria: environment, economy, and corporate. Consequently, it was discovered that infrastructure, green technology, and business continuity consistently held the highest fuzzy weight in multiple sensitivity analysis scenarios. Thus, data center managers can allocate resources based on priority rankings and adjust accordingly.
Keywords: Green Data Center; Sustainability; FAHP; Decision Making.

Abstrak: Pusat data memiliki peran penting dalam penyimpanan dan pemrosesan data di era digital saat ini, sehingga meningkatkan permintaan perencanaan pusat data hijau yang berkelanjutan. Namun, penerapan langkah-langkah praktis untuk mencapai keberlanjutan tetap menjadi tantangan bagi para manajer pusat data. Penelitian ini bertujuan untuk membantu pengambilan keputusan yang terinformasi dalam perencanaan pusat data hijau yang berkelanjutan. Penelitian sebelumnya mengidentifikasi tujuh komponen kunci pusat data hijau: tata kelola TIK, infrastruktur, energi, siklus hidup peralatan, teknologi hijau, standardisasi, dan kelangsungan bisnis. Selanjutnya, penelitian ini melibatkan metode FAHP untuk mengevaluasi perspektif para ahli berpengalaman di industri pusat data. Komponen-komponen pusat data hijau dievaluasi satu sama lain terkait tiga kriteria keberlanjutan: lingkungan, ekonomi, dan tanggung jawab perusahaan. Hasilnya menunjukkan bahwa infrastruktur, teknologi hijau, dan kelangsungan bisnis secara konsisten memiliki bobot *fuzzy* tertinggi dalam beberapa skenario analisis sensitivitas. Dengan demikian, para manajer pusat data dapat mengalokasikan sumber daya berdasarkan peringkat prioritas dan menyesuaikan sesuai kebutuhan.
Kata Kunci: Pusat Data Hijau; Berkelanjutan; FAHP; Pengambilan Keputusan.

INTRODUCTION

The growing trend of digital transformation has led to a significant increase in the volume of data being generated by businesses across all industries. This has resulted in a corresponding rise in demand for data center infrastructure capable of handling the enormous amounts of data being generated. From edge computing to hyperscale cloud, businesses are looking to invest in data center infrastructure that can provide the necessary computing power, storage, and networking capabilities required to support their operations. This demand is projected to continue growing at a significant rate. Globally it is estimated to reach revenues of around $288.300 billion by 2027, growing at a CAGR of approximately 4.900 per cent during the forecast period, driven primarily by the growth of hyperscale cloud providers such as Facebook, Google, Amazon Web Services (AWS), and Microsoft (Arizton, 2022).

Consequently, this entails an inevitable escalation in electricity consumption levels. It is projected that by 2030, data centers will consume approximately 2.130 per cent of the world's total electricity consumption. Unfortunately, most of this energy is dissipated as heat, resulting in 30 per cent of global air pollution (Tian et al., 2021). Numerous studies have been undertaken to identify viable solutions to this issue. One of the studies carried out involves developing a framework for data center managers, encompassing the design, construction, and operational phases, aimed at promoting environmentally sustainable practices.

The Green Data Center framework is a comprehensive approach that comprises seven critical components aimed at promoting environmentally sustainable practices in data centers. The first component is ICT Governance, which involves setting up policies and procedures that govern the use of ICT resources in the data center, such as servers, storage, and networking equipment. Infrastructure component focuses on the design and construction of the physical infrastructure, including the building, power, cooling, and networking systems. Energy is the third component, which involves optimizing energy usage by adopting energy-efficient technologies and practices. Equipment Lifecycle component focuses on managing the lifecycle of the data center equipment, from procurement to disposal, to minimize the environmental impact. Green Technology involves adopting sustainable technologies, such as renewable energy sources and energy-efficient cooling systems. Benchmarking is the sixth component, which involves comparing the data center's energy efficiency and sustainability performance with industry standards and best practices. Finally, Business Continuity involves implementing measures to ensure the data center's resilience and continuity in the face of disruptions. All those components are based on the sustainability concept, which considers the environmental, corporate, and economic aspects of the data center's operation (Ramli and Jambari, 2018).

While the Green Data Center framework provides a comprehensive approach to promoting sustainable practices in data centers, it is important to note that it only provides high-level guidelines. Data center managers often encounter practical challenges in implementing the framework's recommendations, such as determining which components to prioritize based on their specific operational and financial constraints. For example, some data centers may have limitations in adopting renewable energy sources due to location, type of workloads (Hu et al., 2021) or regulatory barriers, while others may face budget constraints in investing in energy-efficient cooling systems (Basmadjian, 2019).

As a result, data center managers must navigate the complex landscape of competing priorities, ensuring that their data centers not only minimize their environmental impact but also remain economically viable and aligned with the organization's overall objectives. Achieving this delicate equilibrium requires careful consideration of energy efficiency measures, cost-effective green technologies, and strategic decision-making to optimize both sustainability and business performance.

To address those challenges, this research takes a unique approach by providing practical decision-making based on predefined components, which hasn't been done before. By evaluating components based on sustainability principles, it will help data center managers to determine the weight value of each component and establish a priority ranking that considers environmental, corporate, and economic aspects. This enables managers to make informed decisions during the planning phase of sustainable green data.

It can also assist data center managers to create efficient and sustainable operations that minimize the environmental impact of their activities, minimize corporate risks, and ensure long-term economic viability. Overall, the evaluation of components based on sustainability principles is essential for the successful implementation of sustainable practices in data centers.

THEORETICAL REVIEW

Green data center. The data center is an essential component of information technology infrastructure that serves to store, process, and manage data for organizations and businesses. However, the significant growth and increasing reliance on data centers have raised concerns regarding their environmental impact. In particular, data centers contribute substantially to carbon dioxide emissions and other environmental burdens.

According to recent estimates, data centers are projected to consume approximately 13 percent of the global electricity demand by 2030 (Aldossary and Alharbi, 2022). This staggering figure highlights the urgent need to address the environmental sustainability of data centers. The environmental impacts of data centers are multifaceted. In addition to their substantial energy consumption, which primarily stems from powering servers, cooling systems, and other infrastructure, data centers also generate significant amounts of heat and contribute to water consumption. The energy-intensive operations of data centers heavily rely on fossil fuel-based electricity, thereby increasing carbon dioxide emissions and exacerbating the challenges associated with climate change.

In response to these concerns, green data centers have emerged as an environmentally friendly solution to reduce the environmental impact of data centers. Green data centers incorporate high-efficiency technologies and practices to lower carbon emissions, minimize energy usage, and enhance energy efficiency. By adopting these measures, green data centers aim to strike a balance between technological advancement and sustainability (Tian et al., 2021).

Several key technologies contribute to the green transformation of data centers. Liquid cooling systems, for instance, provide a more efficient alternative to traditional air conditioning methods, reducing energy consumption and associated emissions (Lai et al., 2023). Additionally, the integration of renewable energy sources such as solar or wind power allows data centers to operate using clean, sustainable energy, reducing their reliance on fossil fuels and further mitigating carbon emissions (Ichinose et al., 2022). Moreover, optimizing server performance and employing more efficient air conditioning systems can significantly contribute to overall energy savings.

Beside the studies on the green data center technology, there is also a study which discusses the importance of capacity planning for sustainability in green data centers. The research highlights the challenges faced by data center managers in balancing capacity requirements and sustainability. The study proposes a practical framework for green data center solutions. The framework includes a description of a data center capacity plan, which establishes the components specific to a Green data center and a set of defined elements that go beyond the conventional technical components, emphasizing sustainability. This validated framework can provide valuable assistance and guidance to practitioners in their capacity planning efforts for green technology. Moreover, it takes into account the environmental, economic, and corporate perspectives, making it a valuable reference for developing practical solutions in the strategic management and operations of a sustainable geen data center.

UNTAR Universitas Tarumanagara
Jurnal Ekonomi e-JE
E-ISSN 2580-4901
P-ISSN 0854-9842

This research acknowledges the significance of adopting sustainable practices in data centers and draws upon a framework proposed by Ramli and Jambari (2018) that comprises seven key components of Green Data Centers. These components are ICT Governance, Infrastructure, Energy, Equipment Lifecycle, Green Technology, Benchmarking, and Business Continuity. **Figure 1** visually represents these components and their interrelationships, serving as a valuable reference for the present study and facilitating the exploration of strategies to enhance the environmental sustainability of data centers.

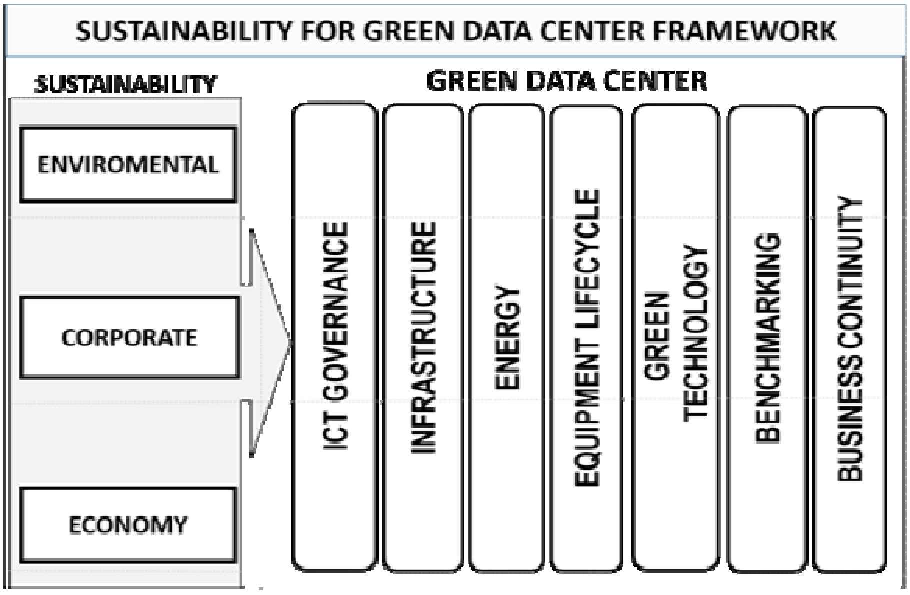

Figure 1. Sustainable Green Data Center Framework
Source: (Ramli and Jambari, 2018)

Fuzzy Analytic Hierarchy Process. The Analytic Hierarchy Process (AHP) is a valuable decision-making technique utilized by individuals or groups to navigate complex decision scenarios. By integrating both qualitative and quantitative criteria, the AHP method facilitates a comprehensive assessment of multiple factors while considering the decision maker's priorities (Özkan et al., 2022). This method incorporates a straightforward model specifically designed to tackle intricate problems and employs a scaling, ranking, or rating scheme to evaluate various intangible variables (Adywiratama et al., 2021). One notable aspect of the AHP method is the utilization of an intangible measure to define the research area and serve as a performance indicator for the project at hand.

In the realm of decision-making processes, the AHP method has emerged as a highly effective tool, particularly in situations involving multiple criteria and alternatives (Githinji et al., 2022). Its ability to encompass diverse considerations and prioritize the decision maker's preferences lends significant support to complex decision scenarios. As such, the AHP method has garnered recognition for its utility and relevance in aiding decision makers in arriving at well-informed and justified conclusions.

The first step in the AHP method is to construct a matrix of obtained pairwise comparison values. Then, the maximum eigenvalue (λmax) is determined for each matrix. The λ_{max} value is needed to obtain the consistency index (CI) value in **Equation 1** and is subsequently used to calculate the consistency ratio (CR) in **Equation 2** that validates that the pairwise comparison matrix has consistent relationships (CR is less than equal to

0.100). The random index (RI) is proportional to the quantity of options or systems under examination. Afterwards, the consistency ratio is computed based on **Table 1**.

Consistency Index

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad \ldots (1)$$

Consistency Ratio

$$CR = \frac{CI}{RI} \quad \ldots (2)$$

Table 1. Random Index (RI)

N (Number of elements)	2	3	4	5	6	7	8
RI (Random Index)	0.000	0.580	0.900	1.120	1.240	1.320	1.410

Source: (Trinh et al., 2022)

The Fuzzy Analytic Hierarchy Process (FAHP) method is a development of the AHP method combined with fuzzy set theory. In the FAHP method, a fuzzy ratio scale is used to indicate the relative influence of related factors, whether they can be directly measured or not. The fundamental difference is the use of numerical scales in pairwise comparisons. AHP uses a scale of 1 to 9, while FAHP uses Triangular Fuzzy Numbers (TFN) denoted by (l,m,u) in **Equation 3** (Narayanamoorthy et al., 2020).

Triangular Fuzzy Number

$$\tilde{A} = (l, m, u); \quad \tilde{A}^{-1} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right) \quad \ldots (3)$$

In the FAHP method, the pairwise comparison matrix is constructed using TFNs, which allows for more flexibility in capturing uncertainty and vagueness in decision-making processes. The TFNs represent three values: the lower (l), the modal (m), and the upper (u) value of support $\tilde{A}$ (Ghoushchi et al., 2021). These values are used to calculate the weights of the criteria, which reflect the relative importance of each criterion in the decision-making process.

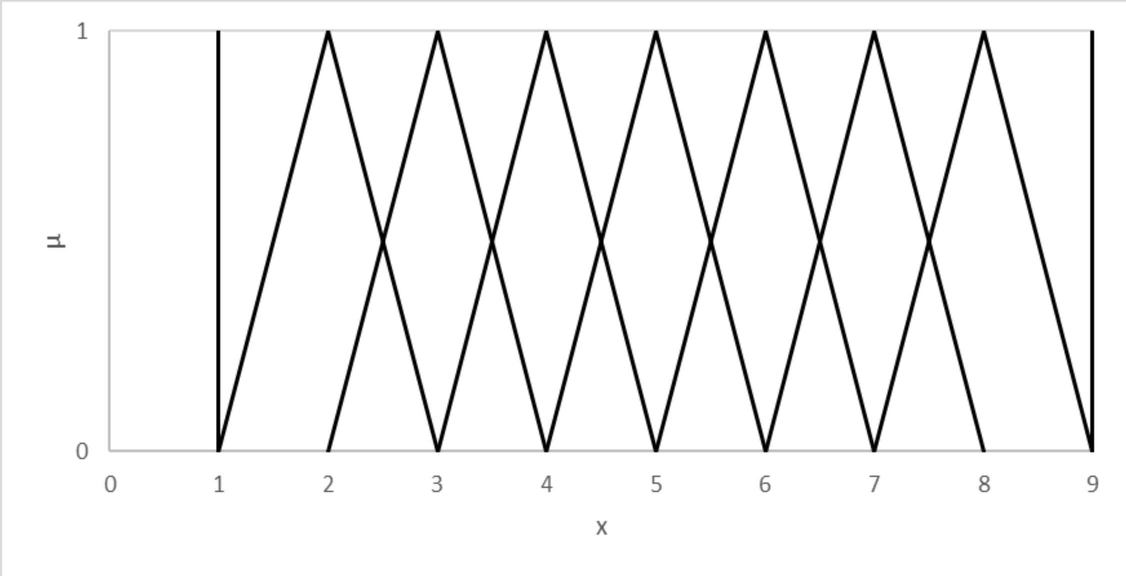

Figure 2. Triangular Fuzzy Number
Source: (Author, 2023)

The AHP scale was converted into TFN as shown in **Figure 2** as the purpose to incorporate the value of uncertainty (between 0 and 1) from the obtained data. Once the pairwise comparison matrix is derived in the form of triangular fuzzy numbers (TFN) which is shown in **Table 2**, the geometric mean value ($\tilde{r}_i$) for each element is computed using **Equation 4**. This step allows for the determination of a representative value that captures the relative importance or priority of each element. Subsequently, the fuzzy weight ($\widetilde{w}_i$) is determined by applying **Equation 5**. The fuzzy weight reflects the significance or influence of each element in the decision-making process. Finally, the weight for each element is obtained by employing the center of area calculation, as specified in **Equation 6**. This calculation method considers the range and spread of the fuzzy numbers to assign weights that appropriately represent the importance of each element in the decision-making process.

Geometric Mean Value

$$\tilde{r}_i = \tilde{A}_1 \otimes \tilde{A}_2 \quad (4)$$

Fuzzy Weight,

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 + \cdots + \tilde{r}_n)^{-1} \quad (5)$$

Weight

$$w_i = \frac{\widetilde{w}_i}{3} = \frac{(l+m+u)}{3} \quad (6)$$

The FAHP method has been widely applied in various fields, including environmental management, finance, and engineering. Its ability to handle uncertain and imprecise information makes it particularly useful in complex decision-making situations where multiple criteria need to be considered by evaluating experts' consensuses (Al Khoiry et al., 2022). However, it is important to note that the FAHP method requires expert judgment in constructing the pairwise comparison matrix, and the results may be sensitive to the choice of TFNs and the expert's subjective opinions. Overall, the FAHP method provides a more flexible and comprehensive approach to decision-making than the AHP method alone, particularly in situations where uncertainty and imprecision are significant factors.

Table 2. AHP to TFN Scale Conversion

AHP Scale	TFN	Invers TFN
1	(1,1,1)	(1,1,1)
2	(1,2,3)	(1/3,1/2,1)
3	(2,3,4)	(1/4,1/3,1/2)
4	(3,4,5)	(1/5,1/4,1/3)
5	(4,5,6)	(1/6,1/5,1/4)
6	(5,6,7)	(1/7,1/6,1/5)
7	(6,7,8)	(1/8,1/7,1/6)
8	(7,8,9)	(1/9,1/8,1/7)
9	(9,9,9)	(1/9,1/9,1/9)

Source: (Al Khoiry et al., 2022)

Sensitivity Analysis. Sensitivity analysis (SA) involves examining how the "outputs" of a "system" are impacted by its "inputs" (Razavi et al., 2021). It is a useful tool for determining how much a model's conclusions depend on its underlying assumptions and parameters. Sensitivity analysis aims to balance the comprehensiveness and interpretability of a model, considering the complexity of the model and the quality of the data used to build it. In essence, sensitivity analysis is like interpreting the meaning of a mathematical model, uncovering the message conveyed by the model's formalism and algorithms. This approach is applicable to various situations where model quality is a concern (Saltelli et al., 2021).

This sensitivity analysis aids decision-makers in understanding the potential variability and uncertainty associated with the selection of components for optimizing the design of a green data center. By assessing the sensitivity of the results to changes in the fuzzy weight values, decision-makers can gain a deeper understanding of the decision-making process and identify any potential risks or vulnerabilities.

Consequently, the sensitivity analysis serves as a vital step in the evaluation of the decision-making process, contributing to a more comprehensive understanding of the implications and significance of the fuzzy weight values assigned to the criteria. This analysis provides decision-makers with valuable insights that can inform their final decisions and enhance the overall reliability and validity of the decision-making process in the context of designing a sustainable and efficient green data center.

METHODS

The research consists of two stages of analysis. The first stage is descriptive analysis, which aims to describe and explain the weight values of the FAHP hierarchy towards sustainable green data center goals. The next stage is prescriptive analysis, which involves analytical models to assist decision-makers in making decisions. In this case, the decision to be made is the design of a sustainable green data center based on environmental, corporate, and economic criteria.

Table 3. Pairwise Comparison

Numerical Value	Importance Level	Explanation
1	Equal	Both activities contribute equally to the objective
2	Weak or slight	Intermediate importance between 1 and 3
3	Moderate	Experience and judgment slightly favor one activity the other
4	Moderate plus	Intermediate importance between 3 and 5
5	Strong	Experience and judgment strongly favor one activity the other
6	Strong plus	Intermediate importance between 5 and 7
7	Very strong or demonstrated	One activity is favored very strongly over the other; its dominance demonstrated in practice
8	Very, very strong	Intermediate importance between 7 and 9
9	Extreme	The evidence favoring one activity over the other is of the highest possible order of affirmation

Source: (Jarek, 2016)

This study uses primary data collection techniques through a questionnaire that be given directly or online to employees from each company in Indonesia that has a data center or is related to the data center industry. These employees hold positions no less than a manager and are directly involved in operational activities, design, or construction of data centers.

AHP is a Multi Criteria Decision Making quantitative technique that utilizes pairwise comparison, contrasting it with direct weighting, to evaluate each alternative or criterion (Dodevska et al., 2023). The questionnaire is prepared using pairwise comparison in **Table 3** as it explains that the meaning of the scale. Higher the value means that the importance level of one component is much higher than the other one. The relation between components for the pairwise comparison is described by the AHP hierarchy in the **Figure 3**. Explanations of the meaning of each Alternatives (Green Data Center Component) in **Table 4** are also provided to each respondent to ensure they have the same understanding.

UNTAR Universitas Tarumanagara
Jurnal Ekonomi
e-JE
E-ISSN 2580-4901
P-ISSN 0854-9842

Table 4. Green Data Center Component

Component	Description
ICT Governance	Governance and guideline; Environmental quality and standards; Data center utilization, operation and planning
Infrastructure	Green best practices; Data center components
Energy	Renewable energy; Energy management
Equipment Lifecycle	Mean time between failure; Equipment replacement
Green Technology	Green procurement; Green equipment and service
Benchmarking	Measurement; Metrics; Green certification
Business Continuity	Sustainable site; Business continuity plan

Source: (Ramli and Jambari, 2018)

Once the pairwise comparison matrix is generated from the questionnaire data and successfully passes the consistency ratio test, the Analytic Hierarchy Process (AHP) scale is transformed into Triangular Fuzzy Numbers (TFN). This conversion enables a more comprehensive representation of uncertainty and imprecision in the decision-making process. Subsequently, the fuzzy weights and actual weight values for each method are calculated utilizing the center of area calculation method.

The center of area calculation provides a means to determine both the fuzzy weights and actual weight values for the criteria and alternatives under consideration. By considering the range and spread of the TFN, the center of area calculation ensures that the resulting weights accurately capture the significance and influence of each criterion or alternative.

After obtaining the fuzzy weights and actual weight values, they are combined to derive priority values. These priority values reflect the relative importance or feasibility of each component in optimizing the design of a green data center that aligns with sustainability aspects. It is important to note that a higher priority value indicates a greater desirability or suitability of a particular component in achieving the sustainability objectives of the data center design.

Based on the priority values, data center managers are empowered to make informed decisions regarding the selection of components to be included in their data center design. By considering the higher-priority components, managers can prioritize the allocation of resources, investment, and efforts towards those areas that have a more substantial impact on achieving a sustainable and environmentally friendly data center.

This systematic approach enables data center managers to effectively evaluate and compare the feasibility and impact of various components within the context of sustainability. By incorporating these priority values into the decision-making process, managers can make informed choices that optimize the design of their green data centers, aligning with their sustainability objectives and enhancing overall environmental performance.

UNTAR Universitas Tarumanagara
Jurnal Ekonomi
e-JE
E-ISSN 2580-4901
P-ISSN 0854-9842

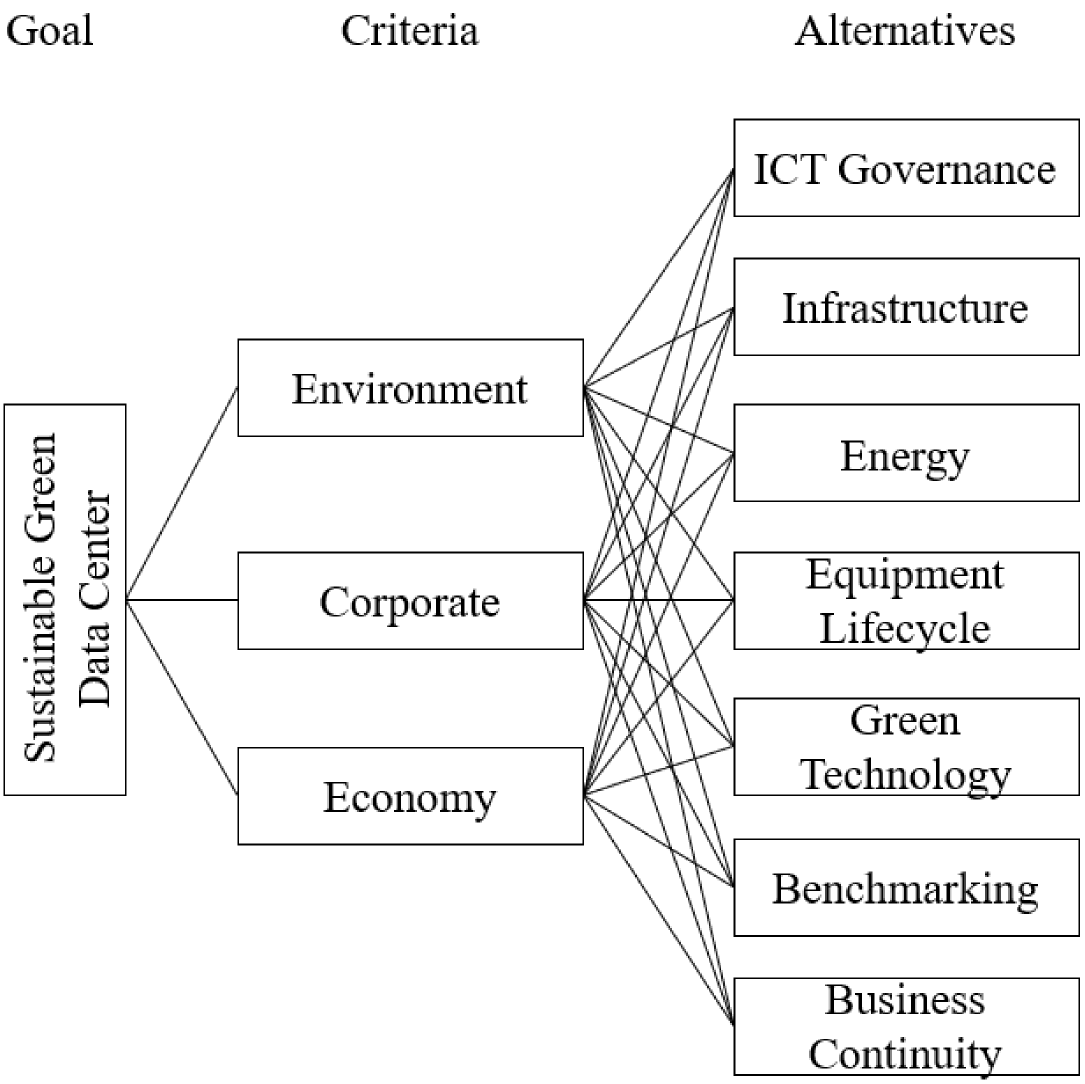

Figure 3. AHP Hierarchy
Source: Author (2023)

Nevertheless, prior to reaching definitive conclusions, an additional crucial step must be undertaken, known as sensitivity analysis. The purpose of this analysis is to assess the extent to which modifications in individual parameters impact the overall results. Specifically, in this sensitivity analysis, the parameter under scrutiny is the fuzzy weight value assigned to the criteria.

To conduct the sensitivity analysis, changes are introduced to the fuzzy weight values assigned to the criteria. Three distinct cases are considered, each assigning a different fuzzy weight value to the criteria. By examining multiple cases, if the three components with the highest weights consistently differ across the cases, the determination of the fuzzy weight value for the criteria becomes even more critical.

The objective of the sensitivity analysis is to evaluate the stability and robustness of the decision-making process in the face of variations in the fuzzy weight values. By observing how the selection of components changes with varying fuzzy weight values, insights can be gained into the relative influence of different criteria and the potential impact of variations in their weights on the final results.

UNTAR Universitas Tarumanagara
Jurnal Ekonomi e-JE
E-ISSN 2580-4901
P-ISSN 0854-9842

RESULTS

This study involved five data center managers with more than 10 years of experience in data center design and operation in Indonesia. These managers were selected based on their expertise, as demonstrated by their certifications and achievements in their current positions. Their experience and capabilities were expected to contribute to the quality of the responses to the Analytical Hierarchy Process (AHP) questionnaire used in this study.

The questionnaire was administered separately to each respondent (as indicated R1 to R5 in the table), with a detailed discussion of the research objectives and the questionnaire method. If the responses did not meet the consistency ratio criteria, further discussion was conducted to review and revise the answers. As a result, the data obtained were ensured to have a consistency ratio less than equal to 0.100, as calculated using **Equation 1** and **Equation 2**.

Table 5. Normalized Fuzzy Weight of Criteria

Criteria	R1	R2	R3	R4	R5	Average
Environmental	0.690	0.122	0.795	0.393	0.750	0.550
Corporate	0.093	0.605	0.123	0.214	0.125	0.232
Economy	0.217	0.273	0.082	0.393	0.125	0.218

Source: Primary data processed

The first set of data analyzed in this study pertains to the sustainable aspect criteria, which includes the environmental, corporate, and economic aspects. The normalized fuzzy weight for each criterion was calculated using **Equation 4** and **Equation 5**. **Table 5** shows the result of the analysis and indicating that the environmental aspect was given the highest weight compared to the other two aspects.

Table 6. Normalized Fuzzy Weight of Alternatives on Environment

Alternatives → Environment	R1	R2	R3	R4	R5	Average
ICT Governance	0.098	0.111	0.159	0.170	0.183	0.144
Infrastructure	0.242	0.150	0.038	0.113	0.044	0.118
Energy	0.069	0.186	0.038	0.188	0.052	0.107
Equipment Lifecycle	0.035	0.050	0.038	0.111	0.053	0.058
Green Technology	0.431	0.086	0.341	0.222	0.244	0.265
Benchmarking	0.065	0.157	0.349	0.082	0.042	0.139
Business Continuity	0.059	0.260	0.037	0.115	0.382	0.171

Source: Primary data processed

UNTAR Universitas Tarumanagara
Jurnal Ekonomi
e-JE
E-ISSN 2580-4901
P-ISSN 0854-9842

Furthermore, the analysis was extended to evaluate each component of the Green Data Center in relation to each criterion of sustainable aspects. **Table 6** presents the normalized fuzzy weight of the alternative components against environmental criteria is presented in and highlight that the green technology component holds the highest weight (0.265) compare to other components, indicating its significant importance in achieving positive environmental impact.

Table 7. Normalized Fuzzy Weight of Alternatives on Corporate

Alternatives → Corporate	R1	R2	R3	R4	R5	Average
ICT Governance	0.235	0.124	0.079	0.167	0.268	0.174
Infrastructure	0.075	0.223	0.287	0.094	0.063	0.148
Energy	0.081	0.133	0.287	0.148	0.050	0.140
Equipment Lifecycle	0.041	0.070	0.025	0.125	0.056	0.063
Green Technology	0.080	0.062	0.025	0.193	0.069	0.086
Benchmarking	0.186	0.096	0.025	0.162	0.053	0.104
Business Continuity	0.303	0.292	0.273	0.111	0.441	0.284

Source: Primary data processed

Table 7 provides the normalized fuzzy weight of the alternative components against the corporate criteria. The outcomes emphasize the pivotal role of the business continuity component, as it holds the highest weight (0.284) in comparison to the other components. This finding underscores the critical significance of ensuring business continuity for the overall sustainability of the corporation. It suggests that maintaining uninterrupted operations and minimizing disruptions is of utmost importance for the long-term viability and success of the organization. The substantial weight assigned to the business continuity component underscores the need for robust strategies and proactive measures to safeguard the corporation's sustainability objectives and mitigate risks that could potentially impede its operations.

Table 8. Normalized Fuzzy Weight of Alternatives on Economy

Alternatives → Economy	R1	R2	R3	R4	R5	Average
ICT Governance	0.070	0.115	0.051	0.119	0.039	0.079
Infrastructure	0.359	0.171	0.233	0.151	0.207	0.224
Energy	0.173	0.137	0.225	0.177	0.239	0.190
Equipment Lifecycle	0.050	0.046	0.229	0.136	0.217	0.136
Green Technology	0.098	0.075	0.022	0.209	0.197	0.120
Benchmarking	0.106	0.131	0.022	0.107	0.022	0.078

UNTAR Universitas Tarumanagara
Jurnal Ekonomi e-JE
E-ISSN 2580-4901
P-ISSN 0854-9842

Business Continuity	0.145	0.324	0.217	0.100	0.080	0.173

Source: Primary data processed

Table 8 presents the normalized fuzzy weight of the alternative components against the economy criteria and reveals that the infrastructure component has the highest weight (0.224) compared to the other components, suggesting its crucial role in achieving cost savings and economic sustainability for the business. This result emphasizes the need for data center managers to prioritize infrastructure investments to ensure efficient and cost-effective operations. The use of high-efficiency and environmentally friendly technologies in infrastructure, such as cooling systems and power distribution units, can lead to significant energy and cost savings while reducing carbon emissions.

Furthermore, the analysis involved combining the weight of alternatives against criteria with the weight of each criterion using **Equation 6**. **Table 9** shows the total weight assigned to each alternative component represents its priority value in the decision-making process. The findings reveal that three alternative components, specifically Business Continuity, Infrastructure, and Green Technology, emerged with the highest weight values. These results signify the significant importance and prioritization of these components in achieving sustainability objectives within the context of the study.

Table 9. Weight of Alternatives on Sustainable Green Data Center

Alternatives	**Environment**	**Corporate**	**Economy**	**Total**
ICT Governance	0.079	0.040	0.017	0.137
Infrastructure	0.065	0.034	0.049	0.148
Energy	0.059	0.032	0.041	0.133
Equipment Lifecycle	0.032	0.015	0.030	0.076
Green Technology	0.146	0.020	0.026	0.192
Benchmarking	0.076	0.024	0.017	0.118
Business Continuity	0.094	0.066	0.038	0.197

Source: Primary data processed

To assess the robustness and sensitivity of the findings, a comprehensive sensitivity analysis was carried out in this study. This analysis involved creating multiple scenarios by modifying the normalized fuzzy weight values assigned to the criteria. Specifically, three distinct scenarios, labeled as Scenario 1, Scenario 2, and Scenario 3, were generated by either exchanging or equalizing the normalized fuzzy weight values obtained from the previous analysis. The results obtained from each of the sensitivity scenarios were compiled in **Table 10**.

Table 10. Normalized Fuzzy Weight of Criteria for Sensitivity Analysis

Criteria	Origin	Scenario 1	Scenario 2	Scenario 3
Environmental	0.550	0.232	0.218	0.333
Corporate	0.232	0.218	0.550	0.333
Economy	0.218	0.550	0.232	0.333

Source: Primary data processed

Following the previous analysis (**Tables 6, 7, and 8**), the subsequent step involved calculating the center of area for the normalized fuzzy weight values for each scenario, utilizing the same set of Alternatives. **Table 11** shows the outcomes of this calculation and reveals that the infrastructure, green technology, and business continuity components consistently emerged with the highest weight values in all three scenarios. This consistency across scenarios provides robust evidence of the significance and prioritization of these three components in the decision-making process.

The repeated identification of infrastructure as one of the top-ranked components underscores its critical role in the sustainable functioning of the data center. Robust infrastructure, encompassing physical facilities, equipment, and logistical capabilities, forms the foundation for efficient and reliable operations. The consistent prioritization of green technology highlights the increasing recognition of its potential to minimize environmental impact and enhance energy efficiency within the data center context. The emphasis on business continuity reaffirms the importance of ensuring uninterrupted operations and mitigating risks that could potentially disrupt critical business processes.

The consistent results obtained across multiple sensitivity scenarios in this study serve to bolster the credibility and reliability of the analysis. These findings are important to data center managers and decision-makers as they offer valuable insights that facilitate effective resource allocation and informed decision-making. This ensures that limited resources are optimally utilized to achieve sustainable and efficient data center operations. The reliability and consistency of these findings provide a solid foundation for decision-makers to make well-informed choices, enabling them to enhance the overall sustainability and performance of their data centers while aligning with organizational goals and objectives.

Table 11. Weight of Alternatives on Sustainable Green Data Center for Sensitivity Analysis

Alternatives	Origin	Scenario 1	Scenario 2	Scenario 3
ICT Governance	0.137	0.115	0.146	0.133
Infrastructure	0.148	0.183	0.159	0.163
Energy	0.133	0.160	0.144	0.145
Equipment Lifecycle	0.076	0.102	0.079	0.085
Green Technology	0.192	0.146	0.133	0.157

UNTAR Universitas Tarumanagara
Jurnal Ekonomi
e-JE
E-ISSN 2580-4901
P-ISSN 0854-9842

Benchmarking	0.118	0.098	0.106	0.107
Business Continuity	0.197	0.197	0.234	0.209

Source: Primary data processed

DISCUSSION

The current research has successfully identified the three components that carry the highest weight value, as evaluated by a panel of authoritative respondents from the data center industry in Indonesia. These respondents, comprising professionals holding influential positions within prominent data center companies as users or consultants, leveraged their extensive experience and expertise to discern these critical components. Their valuable insights and industry knowledge contribute significantly to the determination of priority factors when designing sustainable green data centers.

To ensure the reliability and validity of the analysis process, rigorous testing procedures were implemented. The consistency requirements were meticulously examined to verify the coherence and logical consistency of the collected data. This step was essential in confirming the robustness of the results and minimizing any potential biases or inconsistencies that may have arisen during the data collection and analysis stages.

Furthermore, sensitivity tests were conducted to evaluate the impact of input variations on the results. This allowed for a comprehensive assessment of the stability and reliability of the findings in the face of potential changes in the parameters or weighting values. By subjecting the analysis to these sensitivity tests, the researchers could gauge the responsiveness and resilience of the results, ensuring that they remain valid and trustworthy under different scenarios or conditions.

The findings of this study hold practical implications for data center managers, offering them valuable insights into the prioritization of green data center components. By leveraging these insights, managers can make informed decisions and allocate resources towards the most critical components, thereby reducing energy consumption and operating costs. This, in turn, contributes to the development of sustainable and efficient data center operations. Furthermore, the study sheds light on the key factors that should be taken into consideration during the design phase of sustainable green data centers, aiding managers in developing strategies and approaches that align with environmental sustainability goals.

However, the ultimate question remains whether prioritizing these three components in the design of a data center would indeed result in a green and sustainable data center. Infrastructure is a crucial component in sustainable green data centers. The term refers to the physical and organizational structures necessary for the operation of a data center. This includes power supply, cooling systems, and storage devices, as well as the management and maintenance of these systems. The rising demand for storage capacity and data processing has resulted in data center infrastructures that incorporate more redundant components, which, in turn, consume increasingly large amounts of electricity (Ferreira et al., 2019). Thus, the sustainable design and implementation of a data center's infrastructure can significantly reduce its carbon footprint and increase its energy efficiency. In today's world, where environmental concerns are increasingly urgent, it is essential for data centers to adopt sustainable practices that minimize their impact on the environment.

Green technology is a vital component of sustainable green data centers that are based on environmental, corporate, and economic considerations. Because data centers not only consume significant amounts of energy but also generate carbon dioxide and other IT inefficiencies (Rashid and Noraziah, 2017). Therefore, it is crucial for data center operators to adopt green technology in their operations to ensure their long-term sustainability. This requires investment in the latest green technology solutions and a commitment to continually improving and optimizing operations for maximum efficiency. By adopting green technology, data centers can reduce their environmental impact, improve their corporate social responsibility, and enhance their economic sustainability.

Sustainable green data centers must have robust business continuity plans to ensure that critical business operations can continue without interruption. This requires implementing redundant systems, backup power, and disaster recovery solutions to minimize the impact of any disruptions. These measures not only benefit the environment but also contribute to the economic sustainability of the data center by minimizing downtime and reducing the risk of financial losses. Additionally, the construction of these facilities is often expedited, resulting in exorbitant building costs, and the equipment they house is of high value. Consequently, the selection of suitable locations for data centers requires careful consideration, as stability and security issues are of utmost importance (Lam et al., 2021).

CONCLUSION

The exponential growth of data and the increasing demand for data center services have led to a significant increase in energy consumption and carbon emissions in the information and communication technology sector. As a result, sustainable green data centers have gained significant attention in recent years. Designing sustainable green data centers requires a holistic approach that considers environmental, social, and economic factors. The Fuzzy Analytic Hierarchy Process (FAHP) is a valuable tool that data center managers can use to prioritize sustainable green data center components during the design process.

The FAHP method allows decision-makers to evaluate and rank multiple criteria that affect the selection of sustainable green data center components. The analysis is based on the knowledge and experience of various data center experts and considers the subjective nature of the decision-making process. The results of the analysis based on the FAHP method reveal that Infrastructure, Green Technology, and Business Continuity are the top priority components for sustainable green data centers.

(Wang et al., 2022) introduced a novel energy-efficient cooling method, which exemplifies the rapid advancements in the technology of the data center industry. Regular analyses are imperative to maintain the relevance of the findings. The periodic appraisal and assessment of the FAHP approach could assist data center managers in detecting changes in priorities, emerging challenges, and new opportunities associated with the design of sustainable green data centers.

Apart from the aforementioned considerations, it is crucial to acknowledge that regional or country disparities may influence the generalizability and applicability of the findings derived from the Fuzzy Analytic Hierarchy Process (FAHP) across different regions or countries. The data center industry experiences diverse rates of development and adoption of sustainable practices worldwide, with each region or country facing distinct priorities and challenges concerning sustainability and green technology. Therefore, it is imperative for future research endeavors to take into account these regional or country differences to ensure that the outcomes remain pertinent and applicable to specific geographical contexts.

By recognizing the contextual variations in the data center industry, researchers can refine their methodologies and tailor their approaches to capture the nuances of different regions or countries. This may involve conducting separate studies in various locations or incorporating specific regional factors into the analytical frameworks. For instance, researchers may consider local regulatory frameworks, cultural values, availability of renewable energy sources, or economic conditions that influence decision-making in sustainable data center design and operations. By accounting for these regional or country-specific nuances, the research outcomes can be better aligned with the practical realities and needs of different regions or countries.

To address this issue, future research can employ a focus group discussion approach as been done by (Przewoźna et al., 2022) with a larger and even multi-regional group of respondents before administering the questionnaire. This approach can help identify the specific factors that are most relevant to the data center industry climate in a particular region or country and ensure that the questionnaire is tailored to those specific factors. Moreover, using a larger sample size and including respondents from different regions can ensure that the results are more representative of a broader population.

Furthermore, since sustainable practices are critical for ensuring the long-term viability of data centers, it is important to conduct ongoing research to identify emerging best practices and trends. This research can help data center managers to stay abreast of new developments, while also ensuring that their sustainable green data center components remain relevant and effective. By leveraging the FAHP and other analytical tools, data center managers can make informed decisions that help to reduce energy consumption, improve efficiency, and support the long-term sustainability of their operations.

REFERENCES

Adywiratama, A. D., Ko, C., Raharjo, T., and Wahbi, A. (2021). Critical Success Factors For ICT Project: A Case Study In Project Colocation Government Data Center. *Procedia Computer Science*, *197*. https://doi.org/10.1016/j.procs.2021.12.154.

Al Khoiry, I., Gernowo, R., and Surarso, B. (2022). Fuzzy-Ahp Moora Approach For Vendor Selection Applications. *Register: Jurnal Ilmiah Teknologi Sistem Informasi*, *8*(1). https://doi.org/10.26594/REGISTER.V8I1.2356.

Aldossary, M., and Alharbi, H. A. (2022). An Eco-Friendly Approach For Reducing Carbon Emissions In Cloud Data Centers. *Computers, Materials and Continua*, *72*(2). https://doi.org/10.32604/cmc.2022.026041.

Arizton. (2022). Data Center Market - Global Outlook And Forecast 2022-2027. In *Research and Markets*. https://www.researchandmarkets.com/reports/5550002

Basmadjian, R. (2019). Flexibility-Based Energy And Demand Management In Data Centers: A Case Study For Cloud Computing. *Energies*, *12*(17). https://doi.org/10.3390/en12173301.

Dodevska, Z., Radovanović, S., Petrović, A., and Delibašić, B. (2023). When Fairness Meets Consistency in AHP Pairwise Comparisons. *Mathematics*, *11*(3). https://doi.org/10.3390/math11030604.

Ferreira, J., Callou, G., Josua, A., Tutsch, D., and Maciel, P. (2019). An Artificial Neural Network Approach To Forecast The Environmental Impact Of Data Centers. *Information (Switzerland)*, *10*(3). https://doi.org/10.3390/info10030113.

Ghoushchi, S. J., Osgooei, E., Haseli, G., and Tomaskova, H. (2021). A Novel Approach To Solve Fully Fuzzy Linear Programming Problems With Modified Triangular Fuzzy Numbers. *Mathematics*, *9*(22). https://doi.org/10.3390/math9222937.

Githinji, T. W., Dindi, E. W., Kuria, Z. N., and Olago, D. O. (2022). Application Of Analytical Hierarchy Process And Integrated Fuzzy-Analytical Hierarchy Process For Mapping Potential Groundwater Recharge Zone Using GIS in …. *HydroResearch*. https://www.sciencedirect.com/science/article/pii/S2589757822000026.

Hu, X., Li, P., and Sun, Y. (2021). Minimizing Energy Cost for Green Data Center by Exploring Heterogeneous Energy Resource. *Journal of Modern Power Systems and Clean Energy*, *9*(1). https://doi.org/10.35833/MPCE.2019.000052.

Ichinose, Y., Hayashi, M., Nomura, S., Moser, B., and Hiekata, K. (2022). Sustainable Data Centers In Southeast Asia: Offshore, Nearshore, And Onshore Systems For Integrated Data And Power. *Sustainable Cities and Society*, *81*. https://doi.org/10.1016/j.scs.2022.103867.

Jarek, S. (2016). Removing Inconsistency In Pairwise Comparisons Matrix In The AHP. *Multiple Criteria Decision Making*, *11*, 63–76. https://doi.org/10.22367/mcdm.2016.11.05.

Lai, Y., Fang, X., Han, R., Xuan, Y., and Huang, J. (2023). Design And Key Technology Of The Energy Consumption Management System For The Liquid Cooling Data Center. *Energy Science and Engineering*. https://doi.org/10.1002/ese3.1387.

Lam, P. T. I., Lai, D., Leung, C. K., and Yang, W. (2021). Data Centers As The Backbone Of Smart Cities: Principal Considerations For The Study Of Facility Costs And Benefits. *Facilities*, *39*(1–2), 80–95. https://doi.org/10.1108/F-09-2019-0103.

Narayanamoorthy, S., Anuja, A., Kang, D., Kureethara, J. V., Kalaiselvan, S., and Manirathinam, T. (2020). A Distinctive Symmetric Analyzation Of Improving Air Quality Using Multi-Criteria Decision Making Method Under Uncertainty Conditions. *Symmetry*, *12*(11). https://doi.org/10.3390/sym12111858.

Özkan, B., Erdem, M., and Özceylan, E. (2022). Evaluation Of Asian Countries Using Data Center Security Index: A Spherical Fuzzy AHP-Based EDAS Approach. *Computers and Security*, *122*. https://doi.org/10.1016/j.cose.2022.102900.

Przewoźna, P., Mączka, K., Mielewczyk, M., Inglot, A., and Matczak, P. (2022). Ranking Ecosystem Services Delivered By Trees In Urban And Rural Areas. *Ambio*, *51*(9), 2043–2057. https://doi.org/10.1007/s13280-022-01722-2.

Ramli, S., and Jambari, D. I. (2018). Capacity Planning For Green Data Center Sustainability. *International Journal on Advanced Science, Engineering and Information Technology*, *8*(4). https://doi.org/10.18517/ijaseit.8.4.6417.

Rashid, M., and Noraziah, A. (2017). Review On Green Technology Implementation Challenges In University Data Centre. *Advanced Science Letters*, *23*(11), 11134–11137. https://doi.org/10.1166/asl.2017.10236.

Razavi, S., Jakeman, A., Saltelli, A., Prieur, C., Iooss, B., Borgonovo, E., Plischke, E., Lo Piano, S., Iwanaga, T., Becker, W., Tarantola, S., Guillaume, J. H. A., Jakeman, J., Gupta, H., Melillo, N., Rabitti, G., Chabridon, V., Duan, Q., Sun, X., … Maier, H. R. (2021). The Future Of Sensitivity Analysis: An Essential Discipline For Systems Modeling And Policy Support. *Environmental Modelling and Software*, *137*. https://doi.org/10.1016/j.envsoft.2020.104954.

Saltelli, A., Jakeman, A., Razavi, S., and Wu, Q. (2021). Sensitivity Analysis: A Discipline Coming Of Age. *Environmental Modelling and Software*, *146*. https://doi.org/10.1016/j.envsoft.2021.105226.

Tian, Q., Guo, Q., Nojavan, S., and Sun, X. (2021). Robust Optimal Energy Management Of Data Center Equipped With Multi-Energy Conversion Technologies. *Journal of Cleaner Production*, *329*. https://doi.org/10.1016/j.jclepro.2021.129616.

Trinh, T., Luu, B. T., Le, T. H. T., Nguyen, D. H., Van Tran, T., Van Nguyen, T. H., Nguyen, K. Q., and Nguyen, L. T. (2022). A Comparative Analysis Of Weight-Based Machine Learning Methods For Landslide Susceptibility Mapping In Ha Giang Area. *Big Earth Data*. https://doi.org/10.1080/20964471.2022.2043520.

Wang, X., Liu, Y., Tian, T., and Li, J. (2022). Directly Air-Cooled Compact Looped Heat Pipe Module For High Power Servers With Extremely Low Power Usage Effectiveness. *Applied Energy*, *319*. https://doi.org/10.1016/j.apenergy.2022.119279.