Master's thesis

Master's Programme in Computer Science

Sustainability Evaluation and Metrics in Data Centers: A Multivocal Literature Review

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September 30, 2025

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HELSINGIN YLIOPISTO – HELSINGFORS UNIVERSITET – UNIVERSITY OF HELSINKI

Tiedekunta — Fakultet — Faculty	Koulutusohjelma — Utbildningsprogram — Study programme
Faculty of Science	Master's Programme in Computer Science

Tekijä — Författare — Author

Anne Kuivanen

Työn nimi — Arbetets titel — Title

Sustainability Evaluation and Metrics in Data Centers: A Multivocal Literature Review

Ohjaajat — Handledare — Supervisors

Docent Petri Kettunen

Työn laji — Arbetets art — Level	Aika — Datum — Month and year	Sivumäärä — Sidoantal — Number of pages
Master's thesis	September 30, 2025	44 pages, 14 appendix pages

Tiivistelmä — Referat — Abstract

Introduction: Data centers have expanded significantly in response to the growing global demand for data processing and storage, leading to substantial energy consumption in addition to a range of broader sustainability impacts. Therefore, it is increasingly important to holistically assess the sustainability of data centers. To maintain sustainable and efficient operations, continuous monitoring and precise measurement through various metrics and Key Performance Indicators (KPIs) are essential. This study aims to explore how sustainability is evaluated and measured within data centers.
Methods: A multivocal literature review of formally-published literature (e.g., journal and conference papers) and gray literature (e.g., white papers and annual reports) was conducted. The review included sources from 2010 to 2025, covering a number of 33 sources in total.
Results: Data center sustainability was found to be evaluated across all sustainability dimensions (environmental, economic, individual, social, and technical) with primary focus on the environmental sustainability. Various tools and methodologies were used to evaluate data center sustainability by assessing data center practices or measuring and calculating metrics. Various metrics exist to evaluate data center sustainability, the most frequently used metric being power usage effectiveness (PUE).
Discussion: The findings show that data center sustainability is evaluated by use of various metrics, tools, and methodologies, which alludes to fragmented evaluation practices. The focus on sustainability within data centers has primarily centered on the operational stage and the environmental sustainability through energy efficiency in particular. However, efforts have been made to evaluate environmental impacts more comprehensively by considering the different stages of the life cycle of data centers and a wider range of factors such as carbon emissions, water use, electronic waste, and community impacts.

ACM Computing Classification System (CCS)
General and reference → Document types → Surveys and overviews
Social and professional topics → Professional topics → Computing industry → Sustainability

Avainsanat — Nyckelord — Keywords

sustainability, data centers, metrics, tools, methodologies, multivocal literature review

Säilytyspaikka — Förvaringsställe — Where deposited

Helsinki University Library

Muita tietoja — övriga uppgifter — Additional information

Software study track

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1 Introduction

Sustainability has become an increasingly pressing topic over the years, as people have become more aware of environmental and social issues. According to the United Nations (1987), sustainable development ensures that current needs are met without compromising the future needs of upcoming generations. This is being challenged by climate change, global warming, and the growth of the human population. Over the years, many sustainability initiatives, goals, and policies have been established, concerning companies, organizations and governments. In 2022, the ICT sector was estimated to be responsible for approximately 10% of worldwide electricity consumption (Gelenbe, 2022). In 2017, it was also estimated to contribute approximately 2% of the global carbon dioxide emissions, which is equivalent to the aviation sector (Avgerinou et al., 2017). Thus, it is essential to inspect and discover ways to reduce the significant environmental footprint of the ICT sector.

Data centers consume significant amounts of resources, such as electricity and water, and produce green house gas emissions and electronic waste, contributing to the ICT sector's environmental footprint. As global demand for data processing and storage has grown over the years, data centers are now used in various sectors of the economy, as well as in academic and governmental organizations (Lykou et al., 2018). According to the IEA (2024a), there were more than 8000 data centers worldwide in 2024. This number and data center sizes are expected to increase as the global demand for data processing and storage continues to grow, driven in part by the surge in artificial intelligence (AI) computing (IEA, 2024b).

Technologies such as AI, cryptocurrency mining, and the adoption and expansion of technologies such as 5G networks, cloud-based services and the Internet of Things (IoT), will increase the electricity demand in many regions in the near future (IEA, 2024a). This poses a challenge for data centers to use resources more efficiently while also meeting performance requirements and complying with sustainability policies. Specifically, AI, whose inference and training processes require vast computational resources, is a significant driver in the growth of data centers' energy demand, especially in the United States (U.S. Department of Energy, 2024).

As data centers are expanding, it is important to assess and minimize their environmental impact and ensure sustainable use of resources. To achieve this, while also maintaining effective and efficient operation of data centers, continuous monitoring and accurate measurement through different metrics and Key Performance Indicators (KPI) are crucial (Reddy et al., 2017).

Over the years, numerous studies have explored various ways to improve the efficiency of data center operations, including computing and workload optimization, waste heat reuse, improved cooling strategies, energy-efficient power management, and carbon emission reduction, while less attention has been on the metrics themselves and the holistic evaluation of data center sustainability. This thesis aims to address the research problem of how data center sustainability is evaluated and measured by conducting a multivocal literature review answering the following research questions:

RQ1: What dimensions of sustainability are commonly addressed when evaluating sustainability of data centers?

RQ2: What are the methodologies and tools used to evaluate sustainability in data centers?

RQ3: What are the metrics used to evaluate sustainability in data centers?

The remainder of this thesis is structured as follows. Section 2 explains the background and terms, the concept of data centers and the dimensions of sustainability, how sustainability is evaluated through the use of metrics, and what are the existing sustainability standards, initiatives, and policies involving data centers. Section 3 describes the research method used in detail. The results and answers to the research questions are presented in Section 4. Section 5 discusses the results, examines limitations and threats to validity, and presents suggestions for future work, while Section 6 contains a summary.

2 Background

This chapter provides an overview of data centers and their environmental impacts, followed by an introduction to the concept of sustainability dimensions. Consequently, the existing metrics, standards, initiatives, and policies concerning data centers are presented.

2.1 Data centers

Data center is a term that can be considered from different perspectives, which has lead to varying definitions. Generally, data centers are comprised of the building facility itself and the following subsystems: IT infrastructure, which includes servers, networking and storage devices; cooling infrastructure, which is responsible for preventing the IT infrastructure from being overheated; and power infrastructure, which supplies energy to the IT equipment (Callou et al., 2011).

However, the U.S. Environment Protection Agency, for example, defines a data center as an equipment for processing and storing data, and communications (Geng, 2015). Although data centers can be viewed as facilities or equipment containing miscellaneous co-located servers, according to Barroso et al. (2019) they can also be seen as a warehouse-scale computer (WSC), where clusters of hundreds to thousands of individual servers work together to run software and provide users an internet service, such as web search. This differs from the concept where traditionally data centers host hardware and software, including large numbers of small or medium-sized applications, for multiple organizational units within a company or for altogether different companies, whereas WSCs are owned and operated by single companies such as Google, Microsoft, and Amazon (Barroso et al., 2019). According to Barroso et al. (2019), the WSCs power cloud computing, in which customers can run their applications remotely in the provider's data center without having to manage the hardware themselves.

Furthermore, there are several ways to classify and differentiate data centers such as based on the tier classification of the Uptime Institute and the Telecommunications Industry Association (Barroso et al., 2019), size, location, and ownership. However, to ensure a sufficiently broad search space in this thesis, no distinctions were made between the aforementioned data center concepts or attributes when answering the research questions.

In formally-published and gray literature on the sustainability of data centers, energy consumption often emerges as a key concern. Data centers require large amounts of electricity for computing, cooling, and ICT equipment (IEA, 2024a). According to Geng (2015), typically 45% electrical energy is consumed by ICT equipment and the rest is consumed by facilities such as power and cooling systems, and other supporting infrastructure such as lighting. The IEA (2024a) predicts that the global total energy demand from data centers, AI and cryptocurrencies, could reach more than 1000 Twh in 2026, when in 2022 they had been estimated to consume 460 TwH, which is around 2% of the global demand. According to Barroso et al. (2019), energy management is one of the key issues to consider when it comes to reducing energy-related costs and environmental impacts of data centers.

By consuming vast amounts of electricity, data centers are also one of the significant contributors to the ICT sector's overall greenhouse gas (GHG) emissions (Malmodin et al., 2024). According to Knowles (2021), peer-reviewed studies published since 2015 have generally estimated that the ICT sector's share of global GHG emissions is approximately between 1.8–2.8% . GHG emissions can be categorized into scopes per *the Greenhouse Gas Protocol*, where scope 1 encompasses direct GHG emissions, scope 2 includes indirect GHG emissions from the generation of purchased or brought electricity, while scope 3 covers other indirect GHG emissions from company activities occurring in sources, which are not owned or controlled by the company. Furthermore, data centers' carbon footprint comprises of operational carbon and embodied carbon (Acun et al., 2023). Operational carbon includes emissions from the use stage of data center's life cycle, for example, according to Acun et al. (2023) from electricity use. The embodied carbon also includes emissions from other stages of the life cycle, for example, according to Acun et al. (2023) the emissions generated during the manufacturing of the data center hardware.

In addition to electricity, data centers also consume significant amounts of water. In 2015, data centers were reported to have an estimated annual global water footprint ranging from 767 to 147810 mcm. This includes freshwater consumed and polluted directly by cooling and indirectly through energy consumption. (Ristic et al., 2015). For example, Google's data centers consumed 6.1 billion gallons of water in 2023, which they reported to be 17% more compared to the previous year (Google, 2024). According to Google (2024), the expansion of AI products and services is leading to an increase in their water footprint due to the growing workloads of data centers and the required cooling.

Data centers generate significant amounts of waste heat from the operation of IT equipment and cooling systems (Yuan et al., 2023). Thus, the removal of waste heat is one of the key drivers of data center costs, along with data center design and delivery of input energy (Barroso et al., 2019). Waste heat can also be problematic for the environment, and according to Lam et al. (2021) it can contribute to localized temperature increases, if it is dissipated in the environment. To improve sustainability, different methods have been applied in different applications and scales to utilize waste heat. For example, waste heat can be used for district heating and preheating water in power plants (Wahlroos et al., 2018).

Data centers also contribute to the amount of global electronic waste. In the Global E-waste Monitor 2024 report, it was estimated that in total 62 billion kilograms of electronic waste were produced globally in 2022 (Baldé et al., 2024). When designing a data center, it is often assumed that the equipment, including infrastructure, servers, and network equipment, is new and unused (Redžepagić et al., 2023). Depending on the data centers' facility type, the estimated number of servers per facility differs. For example, in an enterprise-class data center, there can be 800 to 2000 or more servers per facility (Geng, 2015). Manufacturing data centers and the required equipment deplete resources, including minerals and metals (Andrews et al., 2021). The equipment must also be frequently replaced or upgraded during the data center use stage (Murino et al., 2023).

Furthermore, data centers also cause environmental degradation by other means. For example, in order to make space for a data center, deforestation and land clearing may be required (Sovacool et al., 2022). The installation of network cables can also affect local habitats negatively; for example, according to Sovacool et al. (2022), laying subsea network cables can disrupt marine life.

However, assessing the total environmental impact of data centers remains a challenge due to complexity and various influencing factors. For example, while a data center may consume electricity sourced from non-renewable sources, its waste heat can be repurposed for district heating or other purposes, making the overall net environmental effect difficult to quantify.

2.2 Dimensions of sustainability

Over the years, there have been several attempts to define the term sustainability. One way to view sustainability is in terms of dimensions. Originally, the United Nations (1987) have defined the concept of sustainable development in the Brundtland report as such that it ensures that the current needs are met without compromising fulfillment of the upcoming generations' future needs, while also extending the opportunity of bettering life for all equally. This concept includes three dimensions of sustainability that are interdependent: social, economic, and environmental. According to the United Nations (1987), social and cultural aspects determine the needs. However, in places where basic needs are not met, sustainable development cannot happen without economic growth, which involves changes to the physical ecosystem by using non-renewable or renewable resources (United Nations World Commission on Environment and Development, 1987). In addition to social, economic, and environmental dimensions, Goodland and Bank (2002) also mention human sustainability, the private good of individuals.

In software engineering research, in addition to the three dimensions from the Brundtland report, more dimensions have been added later. Penzenstadler and Femmer (2013) introduced a generic sustainability model that can be applied to a product or a company to evaluate their effect on sustainability. This model includes five sustainability dimensions: individual sustainability, social sustainability, economic sustainability, environmental sustainability, and technical sustainability (Penzenstadler and Femmer, 2013). According to Penzenstadler and Femmer (2013), the individual sustainability is about the private good of individuals, such as health and education. The social sustainability is about maintaining social capital and preserving societal communities. An example of this would be considering the effects that software has on society. The economic sustainability is about long-term protection of stakeholders' assets, investments, and value. The environmental sustainability involves protecting natural resources to improve human welfare, for example considering how software affects the environment throughout its life cycle. The technical sustainability aims to keep systems usable and evolving in accordance with the surrounding conditions and requirements in the long term. (Penzenstadler and Femmer, 2013)

Furthermore, Becker et al. (2015) defined five sustainability dimensions in the Karlskrona Manifesto: environmental, social, economic, technical, and individual. Environmental encompasses the effect of human activities on natural systems. Social includes the social communities themselves and the different factors that can affect trust in society. The economic dimension includes assets, capital and added value. Technical includes sustainability or longevity of information, systems and infrastructure in changing conditions. Individual dimension takes into account the individual mental and physical well-being of humans. (Becker et al., 2015).

Based on the concepts of sustainability dimensions, this thesis uses an adapted definition to address the research questions. The dimensions of sustainability are presented in Table 2.1

in no particular order.

Table 2.1: Adapted definition of the dimensions of sustainability for data centers.

Dimension	Description
Environmental	Covers the impact of data centers on the environment throughout their entire life cycle. This includes aspects such as energy consumption, greenhouse gas emissions, water use, electronic waste. It also encompasses strategies for promoting sustainability, such as improving energy efficiency and integrating renewable energy sources.
Social	Involves the effects of data centers on communities and society, including labor practices, working conditions, anticorruption measures, and support for different causes, organizations, or communities.
Economic	Relates to financial aspects of data center sustainability, including stakeholders' assets, investments, and value creation.
Technical	Focuses on operational efficiency, reliability, and security of data centers. It also addresses adaptability and longevity under changing conditions and requirements.
Individual	Emphasizes the physical and mental well-being of individuals working in data centers, including training, health, and safety.

2.3 Sustainability evaluation metrics and standards

According to Reddy et al. (2017), data center operations can be monitored and assessed using metrics and key performance indicators (KPIs). They are essential for ensuring data centers' compliance with sustainability-related reporting, regulations, initiatives, and standards. For example, the Green Grid is an association that has developed several metrics related to data center operations (Table 2.2) and aims to address and offer expertise on data center related issues and improve data center energy, resource efficiency, and sustainability (The Green Grid, 2025).

In addition, there are other measurements for evaluating data center sustainability. For example, the United States Environmental Protection Agency (2018) has defined an Energy Star score to assess data centers' energy performance in relation to its peers. In addition to using the power usage effectiveness (PUE) in its calculation, factors such as climate, location, and business activities at the property are also taken into account (U.S. Environmental Protection Agency, 2018). Furthermore, the United States Green Building Council (USGBC) has developed a sustainable rating system called Leadership in Energy and Environmental Design (LEED) for buildings, which also includes data centers (Brown and Geng, 2015). LEED certification covers sustainability of five main categories: sustainable sites, water efficiency, energy and atmosphere, materials and resource credits, and indoor environmental quality (Matisoff et al., 2014). Depending on the number of points scored for each category, the certification level is certified, silver, gold, or platinum (Matisoff et al., 2014). Motivations to apply for LEED certification include demonstrating that the data center performs as designed and per contract with a focus on availability and redundancy (Brown and Geng, 2015), while also minimizing harmful effects on the environment (Matisoff et al., 2014).

In general, several policies, legislative measures, and initiatives have been established to improve the sustainability of data centers. In 2023, the European Commission presented *the Energy Efficiency Directive* (EED), which includes regulations for the European data center sector to improve transparency and accountability in the data center industry. The EED's Article 12 mandates that starting from 2024, owners and operators of data centers whose power demand is at least 500 kW, are obligated to annually submit KPI measurements related to energy and sustainability (i.e., energy consumption, power utilization, temperature set points, waste heat utilization, water usage, and use of renewable energy) to a designated European database. The EED also refers to *the EU Code of Conduct for Data Centres*, which is an initiative and a guideline that focuses on improving sustainability and data center operations by setting ambitious voluntary standards for companies willing to participate (Acton et al., 2024). KPIs mentioned in the EU Code of Conduct include PUE, carbon usage effectiveness (CUE), and water usage effectiveness (WUE), among other metrics.

Furthermore, the *Climate Neutral Data Centre Pact* initiative sets goals to achieve climate neutrality in the European data center sector by 2030. In the United States, a regulation called the *Energy Act of 2020* requires the federal government to study the energy and water use of data centers and create metrics and good practices to promote efficiency. In China, regulators will require data centers owned by public organizations to improve energy efficiency and be completely powered by renewable energy by 2032. (IEA, 2024a).

In addition, the United Nations (2025) has sustainable development goals (SDG) that also concern data centers. These SDGs include: 6. Clean water and sanitation, 7. Affordable and clean energy, 9. Industry, innovation and infrastructure, 11. Sustainable cities and communities, 12. Responsible consumption and production, 13. Climate action (Hoosain et al., 2023).

Furthermore, the United Nations Global Compact introduced the environmental, social and governance (ESG) framework in *Who Cares Wins* report in 2004. Environmental issues include climate change and related risks, social issues encompass human rights and workplace health and safety, governance issues refer to accountability and transparency in an organization (United Nations Global Compact, 2004). In 2022, the European Commission presented *the Corporate Sustainability Reporting Directive* (CSRD), which requires companies, including data center companies, both within the EU and non-EU companies with substantial EU operations and of certain size, to report their ESG information.

There are various standards regarding data centers that are in effect in the United States, Europe or international level, covering aspects such as data center design, equipment, and occupational health and safety management systems (Manganelli et al., 2021). Specifically, the ISO (the International Organization for Standardization) and IEC (the International Electrotechnical Commission) have published a standard series, the ISO/IEC 30134, which contains KPIs for data centers (Table 2.2).

Table 2.3: ISO/IEC 30134 Series' metrics.

Metric	**Standard**	**Description**
Power Usage Effectiveness (PUE)	ISO/IEC 30134-2:2016	Measures data center energy efficiency
Renewable Energy Factor (REF)	ISO/IEC 30134-3:2016	Percentage of energy from renewable sources
IT Equipment Energy Efficiency for Servers (ITEEsv)	ISO/IEC 30134-4:2017	Average energy effectiveness of all servers or a group of servers in a data center
IT Equipment Utilization for Servers (ITEUsv)	ISO/IEC 30134-5:2017	Average utilization ratio of all servers or a group of servers in a data center
Energy Reuse Factor (ERF)	ISO/IEC 30134-6:2021	Measures the amount of energy reused in a data center
Cooling Efficiency Ratio (CER)	ISO/IEC 30134-7:2023	Measures the efficiency of cooling systems in data center
Carbon Usage Effectiveness (CUE)	ISO/IEC 30134-8:2022	Quantifies operational carbon emissions of a data center
Water Usage Effectiveness (WUE)	ISO/IEC 30134-9:2022	Measures water consumption efficiency in data center

Table 2.2: Examples of Green Grid metrics.

Metric	**Description**
Power Usage Effectiveness (PUE)	Ratio of total facility energy consumed to the energy consumed by IT equipment, indicating data center energy efficiency
Data Center Infrastructure Efficiency (DCiE)	The inverse of PUE, indicating data center energy efficiency
Energy Reuse Effectiveness (ERE)	Measures the efficiency with which waste energy is recovered and reused
Data Center Compute Efficiency (DCcE)	Measures the efficiency of data center's compute resource usage
Data Center Storage Productivity (DCsP)	Ratio of useful storage system work to energy consumed, indicating the energy productivity of storage resources
Carbon Usage Effectiveness (CUE)	Ratio of total operational carbon emissions to the energy consumed by IT equipment
Water Usage Effectiveness (WUE)	Ratio of water consumption to the energy consumed by IT equipment
Electronics Disposal Efficiency (EDE)	Measures how efficiently outdated equipment is disposed of responsibly
Data Center Resource Effectiveness (DCRE)	Assesses the effectiveness and interrelationship of resources used by data centers. Incorporates factors such as energy efficiency, water usage and climate zones

3 Research method

A multivocal literature review (MLR) of both formal literature (e.g., journal and conference papers) and gray literature (e.g., white papers and annual reports) was conducted to answer the research questions presented in Section 1. This was done following the guidelines of Garousi et al. (2019), who adopted the systematic literature review guidelines from Kitchenham and Charters (2007) and extended them to incorporate gray literature. A general overview of the MLR process adapted from Garousi et al. (2019) is shown in Figure 3.1.

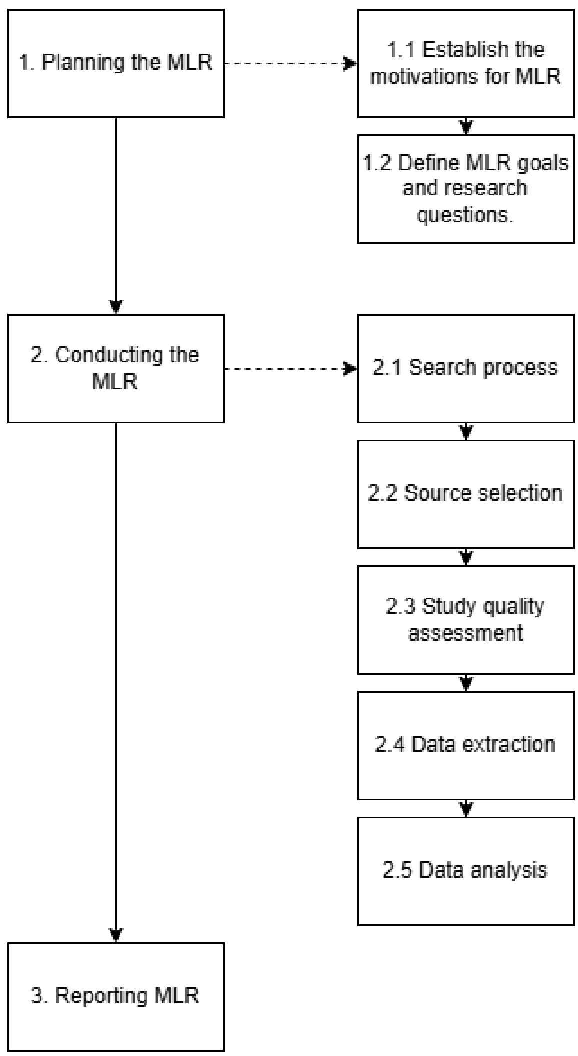

Figure 3.1: General MLR process, adapted from Garousi et al. (2019).

3.1 Research questions

The research problem of how sustainability is evaluated and measured in data centers was addressed through the following research questions presented in Section 1:

> RQ1: What dimensions of sustainability are commonly addressed when evaluating sustainability of data centers?
>
> RQ2: What are the methodologies and tools used to evaluate sustainability in data centers?
>
> RQ3: What are the metrics used to evaluate sustainability in data centers?

RQ1 explores the dimensions of sustainability that are commonly addressed when evaluating the sustainability of data centers. As sustainability itself is a broad and multifaceted concept, its dimensions provide an outline for identifying what sustainability aspects are considered in such evaluations. Understanding this can help identify the scope of current assessments and inform the development of more comprehensive evaluation frameworks.

RQ2 examines the methodologies and tools applied to evaluate the sustainability of data centers. Understanding these approaches can provide information on the practical means by which sustainability assessments are conducted and highlight the potential diversity or alignment of practices within the industry. This knowledge can be useful for identifying best practices, addressing potential gaps, and guiding the selection or development of more effective and consistent evaluation methods.

RQ3 identifies the common metrics used to evaluate the sustainability of data centers. These metrics serve as measurable indicators that operationalize sustainability concepts into concrete criteria, enabling objective evaluation, benchmarking, and monitoring of performance over time. Understanding common metrics gives insight into the priorities and focus areas within sustainability evaluations.

3.2 Search strategy

To identify the relevant search terms, initial exploratory searches were performed on Scopus for formal literature, and Google search engine for gray literature. The initial searches were based on keywords extracted directly from the research questions. The final search queries for both formal and gray literature are presented in Appendix A.

For formal literature, the initial keywords returned relevant results for RQ2 and RQ3. However, with RQ1, the exploratory search revealed that the initial keywords used (e.g., sentence "dimensions of sustainability" or its variations like "dimension of sustainability" and "sustainability dimension") did not yield relevant results. Instead, dividing the research question into several search queries that target a specific dimension of sustainability and using other keywords related to the dimension in question produced more relevant results. For example, when searching for articles on social sustainability and data centers, using keywords such as "social" and "communities" worked better than "social sustainability" or "social dimension". Consequently, Scopus' AI feature was used as a way to generate complementary keywords based on the research questions. Then, few of the resulting articles were examined for relevance and to inform keyword refinement; however, existing keywords were found to be sufficient. Finally, an automatic search was performed on the selected databases (Table 3.1) by combining the search queries into a single query, except in IEEE Xplore, where the wildcard symbol (*) was only applicable when the queries were not combined due to the limit on character count.

For gray literature, initial exploratory searches returned large amounts of results of varying source types and credibility. Including PDF format as a search term in the search string was found to narrow the search space and obtain sources of higher credibility. Varying the order of search terms was also found to result in slight differences in search results. Thus, the order that was deemed to return the most relevant results on the first page was selected for the final search queries. For RQ1 and RQ3, it was determined that annual organizational reports, particularly sustainability reports, were the most relevant sources. As such, the search term "sustainability report" was used in the final search string. For RQ2, exploratory searches revealed that the term "tool" yielded more relevant results from the gray literature compared to "methodology". Therefore, "methodology" was excluded from the final search string.

Furthermore, during exploratory searches for gray literature, it was noted that the most relevant results usually appeared on the first few pages. To restrict the search space, a stopping rule was applied, in which the search results on each page were examined until the results did not look relevant or contribute with new information. Inclusion and exclusion criteria were also simultaneously assessed during this gray literature search process.

3.3 Search scope

For formal literature searches, Scopus and Web of Science were chosen, as they contain multidisciplinary research literature and advanced query options for searching and filtering. In addition, the ACM digital library and IEEE Xplore were chosen for additional coverage.

Table 3.1: Searched databases for formal literature.

Database	**Number of search results with filters**[1]
Scopus	134
Web of Science	30
IEEE Xplore	53
ACM Digital Library	43
Total	260

[1] In the ACM Digital Library, the “Research Articles” content type filter was applied. In the other databases, filters were incorporated directly into the search queries (Appendix A.2).

During planning, it was noted that the formal literature would be complemented by gray literature to ensure that knowledge from practice would not be excluded. Thus, the Google search engine was chosen for the search of gray literature.

3.4 Search process

A search process similar to Garousi et al. (2019), as depicted in Figure 3.1, was carried out. First, the research questions and the aim were defined during the planning phase. After planning, a multivocal literature review was conducted. Relevant source types and data sources were identified, and exploratory searches were conducted for both formal and gray literature to establish the search strings.

First, a search for formal literature was conducted in March 2025. The BibTeX files from sources were exported from the chosen databases. Using BibTeX Tidy, the files were then merged and duplicates were removed. Consequently, inclusion and exclusion criteria were applied based on title, keywords, and abstract. Subsequently, full-text articles were downloaded and evaluated against the criteria, which narrowed the pool of formal literature down to 24 sources.

For gray literature, the search was performed simultaneously with the implementation of inclusion and exclusion criteria in April 2025. At that time, the Google search engine returned about 1 090 000 results for the first search string and about 828 000 results for the second search string. The queries are presented in Appendix A.1. Applying the stopping rule discussed in Subsection 3.2 resulted in nine sources from gray literature. The final pool comprised a total of thirty-three sources from which the data was extracted, analyzed, and reported.

3.5 Inclusion and exclusion criteria

The inclusion and exclusion criteria were used to identify relevant sources to answer research questions. In order for a source to be included in the final pool, it had to pass both inclusion and exclusion criteria. The inclusion criteria were the following:

> I1: The source focuses on the evaluation of the sustainability of the data center at a facility level, specifically discussing one or more of the following: (RQ1) data center sustainability (dimensions of sustainability being environmental, technical, individual, social, and economic), (RQ2) methodologies or tools for evaluation, and/or (RQ3) metrics used for evaluation.
>
> I2 (formal literature): The source is a peer-reviewed original journal or conference paper and not a review, survey, or summary.
>
> I3 (formal literature): The research methods include experiment, case study, interview, or questionnaire survey, and real-world data is used to draw insights. For example, a simulation experiment or conceptual case study that uses real-world data would also be included. Furthermore, case studies that are comparative would also be included.
>
> I4 (gray literature): For RQ1 and RQ3, sources of high and moderate credibility were included, such as white papers and organizational sustainability reports. For RQ2, sources of lower credibility were also accepted due to the potential commer-

cial context of the tools. Examples of acceptable sources include manuals, guides, technical brochures, evaluation checklists, and press releases.

Exclusion criteria:

E1: Duplicates.

E2: The source is not in English.

E3: The source's peer-review status cannot be explicitly determined.

E4: (formal literature): The source's full-text cannot be accessed with Helsinki University credentials.

E5: (gray literature): The source is not in PDF format.

E6: Sources focused only on data center subsystems (IT infrastructure, cooling infrastructure, and power infrastructure) or its specific component will be excluded.

E7: Sources focusing primarily on the development or evaluation of interventions, such as algorithms or operational techniques (e.g., workload schedulers), are excluded, even if metrics related to sustainability are reported.

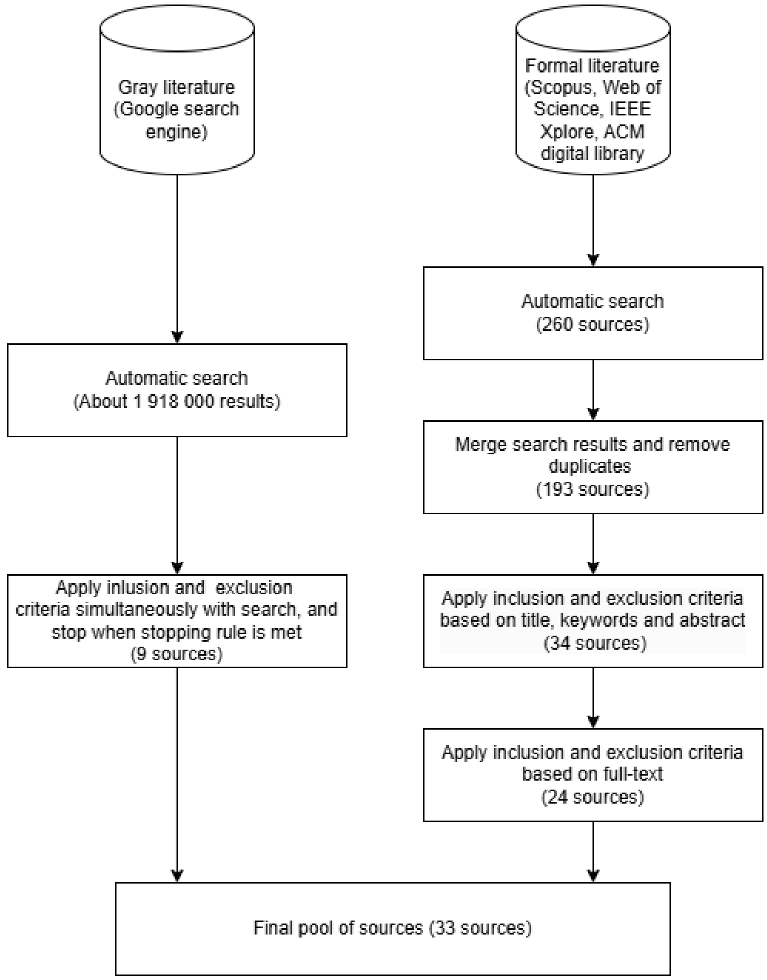

Figure 3.2: The search process.

3.6 Quality assessment

Checklists were used to assess the quality of the sources in the final pool. A checklist of questions for the evaluation of gray literature was adapted from Garousi et al. (2019) as shown in Table 3.2. Consequently, each response was assigned a value (1 for “yes” and 0 for “no”), with the exception of credibility of the source’s outlet type (1 for “High outlet control / High credibility”, 0.5 for “Moderate outlet control / credibility”, and 0 for “Low outlet control / Low credibility”). Finally, two scores were calculated to represent the quality of the sources: the sum of the values and the normalized score, which is the sum of the values divided by the number of quality criteria questions.

The quality criteria for the formal literature were adapted from Dybå and Dingsøyr (2008) as shown in Table 3.3. Each response was assigned a value (1 for “yes”, 0.5 for “to some extent", and 0 for "no"). The values were then summed to establish a score to represent the overall quality of the source.

Quality scores were not used as an exclusion criterion, but as a measure to indicate the level of quality of each source within their respective categories, formal or gray literature.

Table 3.2: Gray Literature Quality Assessment Criteria, adapted from Garousi et al. (2019).

Criteria	**Questions**
Authority of the producer	Q1: Is the publishing organization reputable? (e.g., SEI) Q2: Is an individual author associated with a reputable organization? Q3: Has the author published other work in the field? Q4: Does the author have expertise in the area? (e.g., job title principal software engineer)
Methodology	Q5: Does the source have a clearly stated aim? Q6: Does the source have a stated methodology? Q7: Is the source supported by authoritative, contemporary references? Q8: Are any limits clearly stated? Q9: Does the work cover a specific question? Q10: Does the work refer to a particular population or case?
Objectivity	Q11: Does the work seem to be balanced in presentation? Q12: Is the statement objective or subjective? (1 = objective, 0 = subjective) Q13: Is there vested interest? Are the conclusions free of bias? (1 = no bias, 0 = biased) Q14: Are the conclusions supported by the data?
Date	Q15: Does the item have a clearly stated date? Q16: Have key related grey literature or formal sources been linked to / discussed?
Novelty	Q17: Does it enrich or add something unique to the research?
Outlet type	Q18: **1st tier (1)**: High outlet control / High credibility (books, magazines, theses, government reports, white papers) **2nd tier (0.5)**: Moderate outlet control / credibility (annual reports, news articles, presentations, videos, StackOverflow, Wikis) **3rd tier (0)**: Low outlet control / Low credibility

Table 3.3: Formal Literature Quality Assessment Criteria, adapted from Dybå and Dingsøyr (2008).

Criteria	Questions
Motivation	Q1. Does the study have an explicitly stated or a clear aim?
Context	Q2. Is there an adequate description of the context in which the research was carried out?
Data collection	Q3. Is it clear how data was collected and was the data collected in a way that addressed the research issue?
Data Analysis	Q4. Is there sufficient data analysis presented to support the findings?
Findings	Q5. Are the conclusions clearly stated and justified by the results?
	Q6. Are any limitations explicitly stated and explained?
Novelty	Q7. Does the study enrich or add something unique to the research?

3.7 Data collection and analysis

The data extraction form in Table 3.4 was used for both gray and formal literature. The fields F1—F5 capture general bibliographic information (e.g., publication year, title) that helps to identify and categorize sources. F6-–F7 provide insight into the reliability of the review by distinguishing between formally published and gray literature and by specifying the type of publication. F8—F9 focus on study quality, recording both quality scores and the research methods applied. Finally, F10—F12 are directly related to the research questions: F10 collects the sustainability dimensions and their representative terms, while F11 records the methodologies and tools used, and F12 the metrics employed, both including their labels and brief descriptions.

After the data collection, the data was synthesized descriptively.

Table 3.4: Data extraction form.

ID	**Field**	**Concern/research question**
F1	Author(s)	Documentation
F2	Publication year	Documentation
F3	Title	Documentation
F4	Abstract	Documentation
F5	Keywords	Documentation
F6	Source category (e.g., formal or gray literature)	Reliability of review
F7	Source type (e.g., research article or white paper)	Reliability of review
F8	Quality score	Quality assessment
F9	Research method	Quality assessment
F10	Dimension of sustainability (incl. representative terms)	RQ1
F11	Methodology or tool (label, brief description)	RQ2
F12	Metric(s) (label, brief description)	RQ3

4 Results

This section presents the results of the multivocal literature review. First, an overview of the selected sources is provided in Subsection 4.1. Consequently, the following subsections address the research questions introduced in Subsection 3.1: Subsection 4.2 presents the dimensions of sustainability commonly addressed when evaluating data center sustainability (RQ1); Subsection 4.3 presents the methodologies and tools used to evaluate sustainability in data centers (RQ2); and Subsection 4.4 presents the metrics used to evaluate sustainability in data centers (RQ3).

4.1 Overview of sources

A total of thirty-three sources were selected through the search process. The sources were published during the years 2010–2025. The distribution of formal and gray literature is shown in Figure 4.1. Most of the sources in the final pool originate from formal literature.

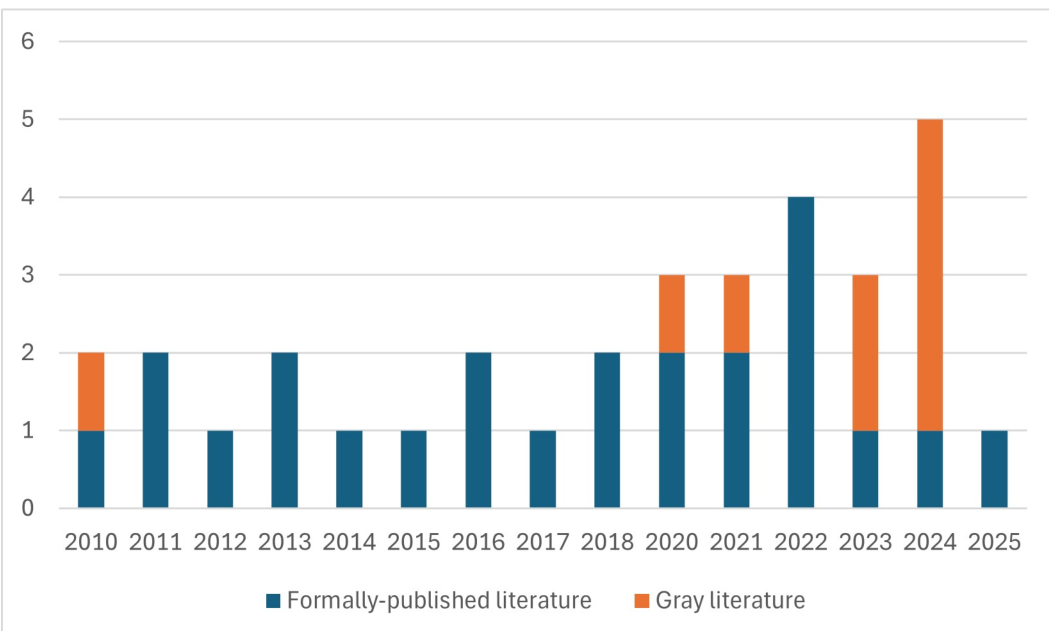

Figure 4.1: Number of sources by publication year.

The source types of gray literature varied, while the formal literature was formed from journal or conference papers, as shown in Figure 4.2. The slightly more common source types for gray literature were white papers and sustainability reports. For formal literature, journal papers were more common than conference papers.

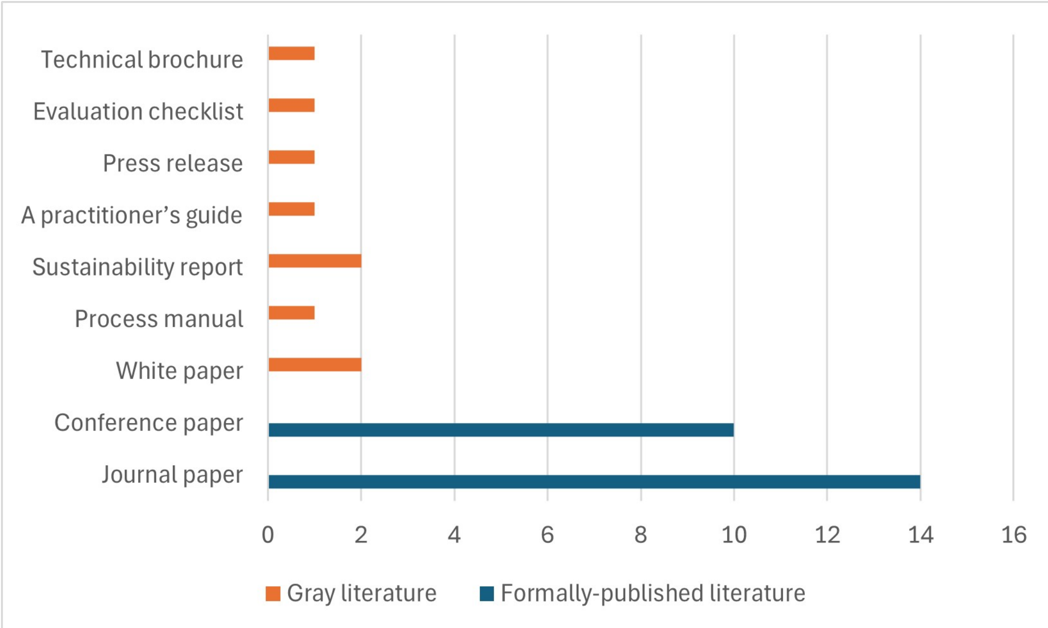

Figure 4.2: Source types by count.

The quality assessment scores for the formal literature are summarized in Figure 4.3 and for the gray literature in Figure 4.4, while more details are provided in Appendix D for the formal literature and Appendix C for the gray literature.

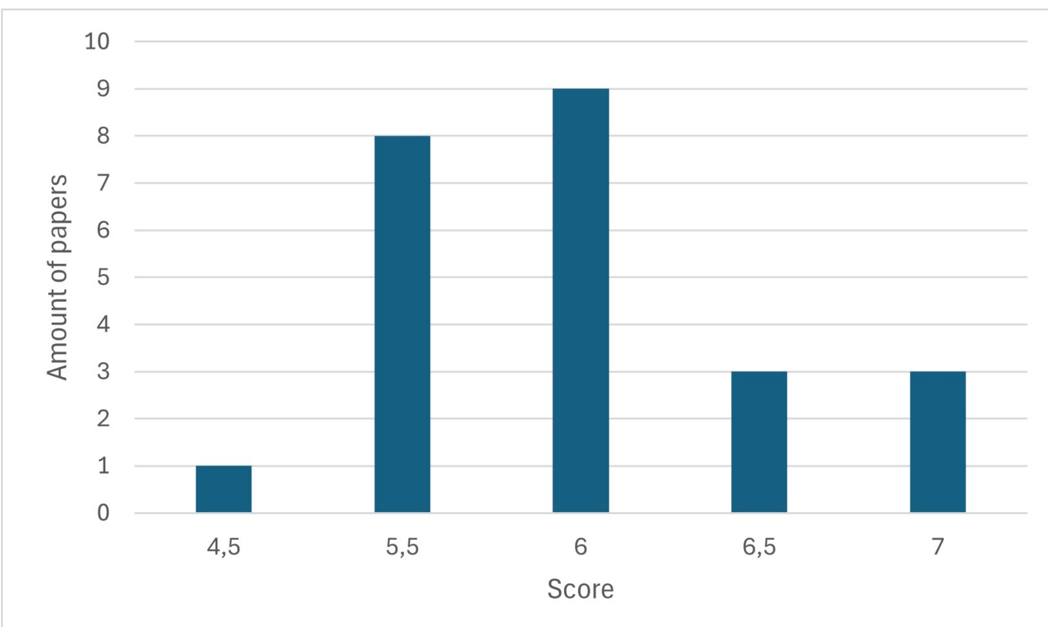

Figure 4.3: Quality assessment scores for formally-published literature.

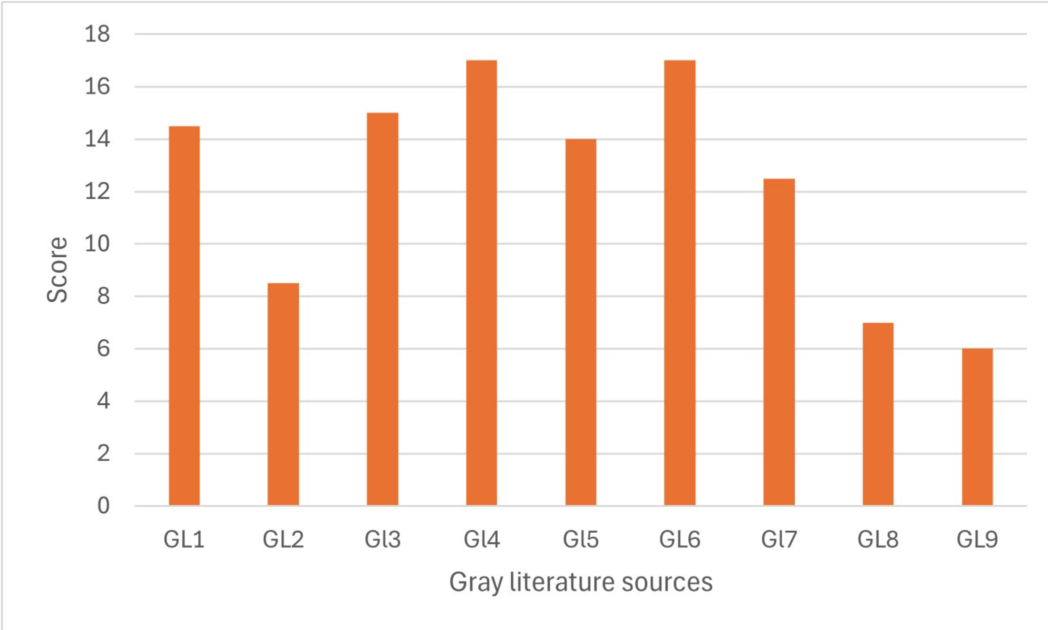

Figure 4.4: Quality assessment scores for gray literature.

4.2 Dimensions of sustainability commonly addressed when evaluating sustainability of data centers

The research question RQ1 “What dimensions of sustainability are commonly addressed when evaluating sustainability of data centers?” was answered by extracting data from field F10 “Dimension of sustainability (incl. representative terms)” (Table 3.4). The results are summarized in Table 4.1 with the identified sustainability dimensions ordered in descending order based on the occurrence, while the representative terms are not in particular order.

The environmental dimension of sustainability was represented in thirty-one sources out of thirty-three. Furthermore, representative terms for environmental sustainability included words such as “environmental”, “green”, and “ecosystem”. For example, in FL1 the authors referred to “environmental sustainability”. In FL1 and FL2, “greening data centers” was discussed. This “greening” involved the implementation of practices that help data centers reduce emissions and manage resources effectively. For example, by increasing the reuse and recyclability of existing materials in data center operations, overall sustainability can be improved. FL12 explored the “environmental footprints” of data centers, while FL21 addressed “environmental concerns”. Sources, which introduced metrics or tools to evaluate data centers, specifically in terms of energy use, water consumption, greenhouse gas emissions, or other impacts on the environment (e.g., acidification or depletion of resources), were also inferred to address the environmental dimension.

The economic dimension was represented in seven sources. Representative terms included words such as “savings”, “cost”, and “net benefit”. FL8 and GL8 referred to potential savings. FL4 examined loss by quantifying carbon emissions from excess energy consumption, i.e. deviation from the ideal benchmark PUE, as USD based on the carbon credit market prices. Meanwhile, FL7 involved consideration of data center facility development cost and FL19 introduced a tool that calculated the annual power cost. Furthermore, FL7 also discussed the maximization of benefits in relation to data center cost while remaining green, and the total life cycle cost of ownership (TCO). In FL8, the total cost of ownership was also mentioned. In GL1, the data centers’ economic performance was measured as the increase in the capacity of installed operational data centers according to the authors. GL5 refers to lifecycle costing as a tool that can be used to evaluate data centers’ economic impact, thus this source was inferred to address the economic dimension.

The technical dimension was represented in five sources. Representative terms included words such as “security” and “resilience”. Specifically, GL1 and GL7 highlighted security and data privacy. In addition, GL7 mentioned their data centers being engineered with multiple levels of redundancy in order to offer reliable service. When evaluating data centers, FL13 and FL23 included considerations related to performance and management of data center equipment. In addition, FL18 introduced metrics (Table 4.3), such as power system reliability, which were inferred to address the technical dimension.

The individual dimension was represented in four sources. Representative terms included words such as “health”, “training”, “well-being”. Each of the four sources (Table 4.1) included considerations for health. In addition, GL1 and GL7 also mention training and the well-being of data center employees.

The social dimension was represented in four sources. Representative terms included words such as “communities” and “anti-corruption”. FL18 examined the community acceptance and community impacts of Nordic data centers. Similarly, FL21 also explored the community impacts of data centers in the Nordics. Furthermore, GL1 and GL7 included metrics (Table 4.3) such as community impact, incidents of corruption, and ethics and anti-corruption training participation, which were inferred to address the social dimension.

Table 4.1: Dimensions of sustainability commonly addressed when evaluating sustainability of data centers.

Dimension	Representative Terms	Number of sources	Sources
Environmental	Power usage effectiveness (PUE), carbon usage effectiveness (CUE), water usage effectiveness (WUE), environmental, green, greening, environmental sustainability, sustainability performance, carbon, emission, green house gases, water, waste, energy, resources, ecosystem	31	FL1, FL2, FL3, FL4, FL5, FL6, FL9, FL10, FL11, FL12, FL13, FL14, FL15, FL16, FL17, FL18, FL19, FL20, FL21, FL22, FL23, FL24, GL1, GL2, GL3, GL4, GL5, GL6, GL7, GL8, GL9
Economic	Savings, cost, loss, total cost of ownership (TCO), net benefit, economic, economic performance	7	FL4, FL7, FL8, FL19, GL1, GL5, GL8
Technical	Security, data privacy, performance of equipment, management of equipment, resilience	5	FL13, FL18, FL23, GL1, GL7
Individual	Health, training, well-being	4	FL17, FL22 , GL1, GL7
Social	Communities, community acceptance, community impact, anti-corruption, net promotes score (NPS)	4	FL18, FL21, GL1, GL7

4.3 Methodologies and tools used to evaluate sustainability in data centers

The research question RQ2 "What are the methodologies and tools used to evaluate sustainability in data centers?" was answered by extracting data from field F11 "Methodology or tool (label, brief description)" (Table 3.4). Several methodologies and tools were found to be used to evaluate data center sustainability. Many of these can be adapted to address different sustainability dimensions depending on their design and content. Therefore, Table 4.2 presents the tools and methodologies without assigning them to specific sustainability dimensions, while the rest of this subsection explains the context in which they were used. The results in Table 4.2 are summarized in no particular order.

In FL1, a methodology was introduced for data center practitioners to evaluate their green information systems (IS) practice. According to the authors, Green IS practice includes actions such as reducing carbon dioxide emissions, preventing water pollution, and managing energy, water, and waste in a sustainable manner. In FL2, sustainable practices were instead called green computing life cycle strategies, which included managing energy sustainably and also procuring, recycling, refurbishing, and disposing of equipment in an environmentally friendly manner. These practices were then evaluated against a specific set of metrics targeted for green computing life cycle strategies. FL1 and FL2 were categorized under “Green Practices Evaluation” in Table 4.2 due to similar concepts.

In FL4, a methodology for evaluating data center sustainability performance using the Taguchi loss function was introduced. It shows how excess energy consumption, reflecting poor sustainability performance and deviation from the ideal PUE benchmark, translates into loss. This loss is measured using a carbon emission metric and is quantified economically by converting the emissions into currency values based on the carbon credit market prices. In FL20, cost-benefit analysis was used to evaluate whether implementing certain solutions towards a green data center may have significant associated costs for the data center, while also providing insight on the current situation.

Energy Efficiency Analysis (FL8 and GL3) included an in-depth analysis of the different components of data center energy consumption. These components include IT equipment, cooling, and power systems that support IT equipment. In FL10, data envelopment analysis (DEA) was used to analyze the green energy efficiency of data centers, where green energy efficiency refers to the proportion of renewable and bioenergy used relative to energy consumption. For this, a DEA-based model was constructed, which evaluates energy efficiency using multiple inputs and outputs. The input module includes energy and capital inputs, while the output module includes economic and product outputs.

To evaluate a data center’s sustainability throughout its entire life cycle, from manufacturing, operation to demolition and dismantling, Life Cycle Assessment (LCA) can be used to evaluate the environmental, social, and individual sustainability (FL17 and FL22), while Lifecycle Costing can be used to evaluate the economic sustainability of buildings and constructed assets and their parts, including data centers (GL5).

Sustainability rating systems for buildings, such as the LEED and the Building Research Establishment Environmental Assessment Method (BREEAM) mentioned in GL5, can also be used to evaluate data center sustainability. In FL13, a sustainability evaluation model, which integrates multiple criteria decision-making methods, was used to evaluate and compare big data center performance, including aspects such as energy and cooling.

A sustainability assessment tool was presented in sources FL1, GL2, and GL8. In FL1, the tool was a collaborative agent-based web architecture that practitioners can use to evaluate, benchmark, and rate their current green IS practice. In GL2, the tool was proposed as a means of assessing sustainability and was structured into categories such as energy use and water use, while covering the entire life cycle of a data center and taking into account aspects such as the local climate and environment. In GL8, tools were introduced that assess the energy use of a data center and identify potential savings opportunities.

In FL9, a sustainability monitoring system was used to evaluate the data center performance developed in the context of the RenewIT European project. The tool was a web-based portal where users could monitor the performance of the data center by selecting the measurements, data, and activities.

FL19 and GL6 presented calculators for assessing sustainability. According to the authors, the *power efficiency measurement calculator* (PEMC) helps data center managers assess the performance and efficiency of their data centers (FL19). The calculator measures PUE, DCiE, total costs incurred, and carbon dioxide emissions, while GL6 presented a calculator that estimates a data center's life cycle carbon footprint called the *Data Center Lifecycle CO2e Calculator*.

To evaluate data center practices in FL23, the practices of two data centers were compared with each other and evaluated against the best practices outlined in the EU Code of Conduct by using a checklist. This checklist covered areas such as data center utilization, management and planning, equipment, and monitoring. Furthermore, GL9 introduces a checklist designed to ensure that data center providers meet operational requirements and sustainability goals, addressing areas such as energy, water, and waste management, as well as employee and community engagement to promote sustainability awareness.

Table 4.2: Methodologies and tools used to evaluate sustainability in data centers.

	Number of sources	Sources
Methodologies		
Green Practices Evaluation	2	FL1, FL2
Taguchi-Based Method for Assessing Data Center Sustainability	1	FL4
Energy Efficiency Analysis	2	FL8, GL3
Data Envelopment Analysis (DEA)	1	FL10
Cost-benefit Analysis	1	FL20
Life Cycle Assessment (LCA)	2	FL17, FL22
Lifecycle Costing	1	GL5
Sustainability Rating System for Buildings	1	GL5
Multiple-criteria Decision-making Model (MCDM)	1	FL13
Tools		
Sustainability Assessment Tool	3	FL1, GL2, GL8
Sustainability Monitoring System	1	FL9
Sustainability Calculator	2	FL19, GL6
Sustainability Checklist	2	FL23, GL9

4.4 Metrics evaluating sustainability of data centers

The research question RQ3 "What are the metrics used to evaluate sustainability in data centers?" was answered by extracting data from field F12 "Metric(s) label, brief description" (Table 3.4). There are many metrics that measure the sustainability of data centers. The complete list is presented in Table 4.3, where each metric is classified into a category of a sustainability dimension and in no particular order.

The environmental metrics can be organized into subcategories, which are related to energy, carbon dioxide or green house gases, water, waste, and other effects on the environment (e.g., outdoor noise or mean species abundance). In addition, FL2 presented a set of *Green Metrics* to evaluate the extent to which the life cycle strategies introduced in Section 4.3 are applied in a data center, reflecting its sustainability. For energy, the metrics focus on energy efficiency, consumption, and renewable energy. In the formal literature, new energy metrics were also proposed in FL3 and FL14 and both utilized the concept of PUE.

The metrics for carbon dioxide and green house gases were varied. Carbon dioxide was reported either in units (e.g., kilograms) or through the following indicators: CUE (FL6, GL4), the Annual Carbon Footprint (FL19; calculated based on carbon emissions produced per kilowatt hour of electricity), carbon intensity of operations (GL1), or carbon offset credits (GL1). Green house gases were divided into scopes 1, 2, and 3. There were slight differences in the units in which both carbon dioxide and green house gases were reported.

The water metrics focused on consumption, while the waste metrics focused on the generation and diversion of both e-waste and general waste. In addition, there are metrics that measure other environmental impacts of data centers, such as depletion of natural resources (FL17) and mean species abundance (GL4). In the formal literature, these impacts were taken into account by sources that used LCA (FL17 and FL22). In FL17, the authors selected five environmental impact indicators, which were climate change in units of kg CO2e, depletion of natural resources (minerals and metals), acidification, ionizing radiation, and fine particle emissions. In FL22, the Eco-indicator 99 method was selected for LCA and the authors utilized its two sets of categories. The 11 impact categories were carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals and fossil fuels, while the broader damage categories included resources, human health, and ecosystem quality. Following the Eco-indicator 99 method, the effects were then measured in Eco-indicator points (Pt) according to the functional unit of one kilowatt of IT per year.

The metrics that measured the economic sustainability of data centers were related to cost (FL7, FL19, FL4), savings (FL8) or the utilization and capacity of installed data centers (GL1), whereas the technical metrics focused on operational efficiency, reliability, and security (FL18, GL7). Examples of such metrics include per unit area (PUA), calculated as the average data center space benchmarked against 10,000 square meters, power density (PWD), and power system reliability (PSR), which ranked data centers according to their ability to remain operational during faults (FL18). In addition, security-related metrics were the number of security breaches and the percentage of completed security awareness training (GL7).

The metrics related to the individual dimension focused on health, safety, and training. Health was measured using different units in GL1 and FL22. In FL17, the metric for fine particles was represented by disease incidence. Thus, this metric overlaps the individual and environmental categories, but was classified under the individual category. Other individual metrics were, for example, the lost time incident rate (GL1), the total number of fatalities (GL7), and the percentage of employees who received professional training or development (GL7).

Social metrics focused on customers, employees, and communities. GL7 presented two customer-related metrics: Customer Sustainability Priority and Customer Net Promoter Score (NPS). While the term "Customer Sustainability Priority" was not explicitly defined in GL7, based on the context, it is inferred to represent the percentage of customers who prioritize sustainability in their decision-making, whereas the NPS metric assesses customers' loyalty and likelihood of recommending the business to others. In addition, various employee information was measured, such as gender diversity (GL1) and type of employment contract (GL7). The metrics related to communities were, for example, new jobs created, number of causes or organizations supported, and confirmed incidents of corruption (GL7).

Table 4.3: Metrics evaluating sustainability of data centers.

Metric	Number of sources	Sources
Environmental		
Power Usage Effectiveness (PUE)	17	FL3, FL4, FL5, FL6, FL7, FL8, FL9, FL10, FL11, FL16, FL18, FL19, FL24, GL1, GL4, GL7, GL9
Data Center Infrastructure Efficiency (DCiE)	3	FL5, FL10, FL19
Renewable Energy factor (REF)	1	GL4
Energy Reuse Factor (ERF)	1	GL4
Data Center Energy Productivity (DCeP)	1	FL15
Coefficient of PUE (COPUE)	1	FL3
Green Label towards Energy proportioNality for IaaS DAta centers (GLENDA)	1	FL14
Site Infrastructure Energy Efficiency Ratio (SI-EER)	1	FL20
The Non-Renewable Primary Energy Factor	1	FL9
The Net Import Energy	1	FL9

Metric	**Number of sources**	**Sources**
Total energy (MWh)	1	GL1
Total purchased electricity (MWh)	1	GL1
Total renewable energy share (%)	1	GL1
Electricity consumption (GWh/year)	1	FL12
Renewable energy purchased(Scope 2, MWh)	1	GL1
Renewable electricity procurement	1	GL1
Carbon Usage Effectiveness (CUE)	2	FL6, GL4
The Annual Carbon Footprint	1	FL19
CO2 emissions (CO2 annual, tonne) (kg CO2)	2	FL4, FL9
GHG emissions (Scope 1, 2, 3) (ton CO2e) (tens of tonnes CO2eq/year)	5	FL12, GL1, GL4, GL6, Gl7
Climate change (kg CO2 eq.) (Pt/kW/year)	2	FL17, FL22
Carbon intensity of operations (ton CO2e/MW)	1	GL1
Carbon offset credits (ton CO2e)	1	GL1
Water Usage Effectiveness (WUE)	4	FL5, FL24, GL7, GL9
Water consumption (m3/year)	1	FL12
Water withdrawals for cooling (m3)	1	GL1
Total site water withdrawal (m3)	1	GL4
Total site water consumption (m3)	1	GL4
Total source energy water usage (m3)	1	GL4
Total water use in supply chain (L per product)	1	GL4
Water-free cooling (%)	1	GL1
Waste to Landfill (metric tons)	2	GL1, GL7
Waste diversion (%)	2	GL1, GL4
Total waste generated (metric ton)	1	GL4
E-waste generated (metric ton)	1	GL4
Battery waste generated (metric ton)	1	GL4
Total waste diversion rate (ratio)	1	GL4
E-waste diversion rate (ratio)	1	GL4
Battery waste diversion rate (ratio)	1	GL4

Metric	**Number of sources**	**Sources**
Depletion of natural resources (minerals and metals) (kg Sb eq.)	1	FL17
Resources (Pt/kW/year)	1	FL22
Fossil Fuels (Pt/kW/year)	1	FL22
Minerals (Pt/kW/year)	1	FL22
Ecosystem quality (Pt/kW/year)	1	FL22
Ecotoxicity (Pt/kW/year)	1	FL22
Acidification (mol H+ eq.)	1	FL17
Acidification/Eutrophication (Pt/kW/year)	1	FL22
Ionizing Radiation (kBq U235 eq.)(Pt/kW/year)	1	FL17
Total land use (Pt/kW/year)(m2)	2	FL22, GL4
Land use intensity (kW/m2)	1	GL4
Outdoor noise (dB(A))	1	GL4
Mean species abundance (MSA) (MSA/km2)	1	GL4
Ozone Layer (Pt/kW/year)	1	FL22
Life Cycle Strategies' Green Metrics	1	FL2
Economic		
Total Cost of Ownership (TCO)	1	FL7
Total costs incurred	1	FL19
Taguchi Loss	1	FL4
Annual savings	1	FL8
Installed Data Center Capacity (MW)	1	GL1
Installed Data Center Utilization (%)	1	GL1
Technical		
Per Unit Area (PUA)	1	FL18
Power density (PWD)	1	FL18
Power System Reliability (PSR)	1	FL18
Security breaches (#)	1	GL7
Completion of Security Awareness Training (%)	1	GL7
Individual		

Metric	**Number of sources**	**Sources**
Employees who received professional training or development (%)	1	GL7
Employee health and safety (recordables)	1	GL1
Human Health (Pt/kW/year)	1	FL22
Carcinogens (Pt/kW/year)	1	FL22
Fine particles (Disease incidence)	1	FL17
Respiratory Inorganics (Pt/kW/year)	1	FL22
Respiratory Organics (Pt/kW/year)	1	FL22
Lost Time Incident Rate (LTIR, including contractors)	1	GL1
Total number of fatalities (#)	1	GL7
Social		
Customer Sustainability Priority (%)	1	GL7
Customer Net Promoter Score (NPS)	1	GL7
Employee Information, Headcount permanent (FTE)	1	GL7
Employee Information, Headcount fixed term contract (FTE)	1	GL7
Employees by Gender (FTE)	1	GL7
Return Rate After Parental Leave (%)	1	GL7
Gender diversity (Management Team, %)	1	GL1
New jobs created (#)	1	GL7
Community impact, number of causes or organisations supported (#)	1	GL7
Confirmed incidents of corruption (#)	1	GL7
Ethics & anti-corruption training participation (%)	1	GL1

5 Discussion

In this section, the results presented in Section 4 are discussed. Consequently, limitations and threats to validity are examined. Finally, suggestions for future work are presented.

5.1 Interpretation of findings

For each research question, the results were from both the gray and the formal literature. For the research question RQ1 “What dimensions of sustainability are commonly addressed when evaluating sustainability of data centers?”, it was found that all five dimensions of sustainability were represented (Table 4.1). Some sources addressed multiple dimensions simultaneously, while most focused on a specific dimension. The environmental dimension was addressed in most sources (thirty out of thirty-three), while the economic, technical, individual, and social dimensions were addressed to a lesser extent in comparison.

Furthermore, sustainability dimensions were more commonly represented by a variety of terms that did not include the word “dimension”, with the exception of one source (FL1) referring to the “environmental sustainability” itself. The social dimension was strongly represented by variations of the word “community” compared to other terms, whereas the representative terms for the rest of the dimensions of sustainability appeared to be more evenly distributed.

For the research question RQ2 “What are the methodologies and tools used to evaluate sustainability in data centers?”, a variety of tools and methodologies was found (Table 4.2). No single tool or methodology was clearly more prevalent than the other. Some of the sources focused on evaluating data center practices (e.g., FL1, FL2, FL23, GL9), while others helped measure or calculate certain metrics (e.g., FL19, GL6).

For the research question RQ3 “What are the metrics used to evaluate sustainability in data centers?”, many metrics were found (Table 4.3). The most frequently used metric was PUE, which was represented in seventeen out of thirty-three sources. The novel tools (e.g., sustainability calculators) or metrics (e.g., COPUE and GLENDA) also utilized PUE. Social and individual metrics were found to be more commonly presented in gray literature compared to formal literature, where they were present in the papers using the life cycle assessment methodology. The environmental metrics constituted the largest proportion of all metrics, and thematic categories such as energy, carbon or greenhouse gas emissions, water, waste, and ecosystem impacts, could be identified within it.

In addition, some relevant metrics to data center sustainability were originally presented in Table 2.2 “Examples of Green Grid Metrics” and Table 2.3 “ISO/IEC 30134 Series' Metrics”. Contrary to expectations, many of these metrics were not reported or used as frequently. This raises the question whether this could be due to a lack of transparency in reporting, the commercial and competitive nature of the data center industry, challenges in implementing them in practice, or possibly other reasons.

Regarding the research problem of how sustainability is evaluated and measured in data centers, the findings show that there are various tools, methodologies, and metrics that measure and evaluate data center sustainability. However, this diversity alludes to fragmented evaluation practices. Furthermore, although data center sustainability was found to be evaluated across all the sustainability dimensions, the focus on sustainability within data centers has primarily centered on the operational stage and the environmental sustainability through energy efficiency in particular. Specifically, PUE has maintained its popularity throughout the years. However, efforts have been made to evaluate environmental impacts more comprehensively by considering the different stages of the life cycle of data centers and a wider range of factors, such as carbon emissions, water usage, and electronic waste. Although some consider other factors as well, such as community impacts, environmental sustainability is the most prominently addressed throughout the years.

5.2 Limitations and threats to validity

Given the individual nature of this study as a master's thesis, the multivocal literature review (MLR) process was conducted by a single researcher. This differs from the common practice of involving multiple researchers in systematic literature reviews, which helps to reduce bias and improve reliability (Kitchenham and Charters, 2007). As a result, the decisions made during the process, such as source selection, data extraction, and quality assessment, and also the findings of this MLR may be subject to personal researcher bias and inaccuracies despite the efforts to remain neutral and thorough.

Furthermore, this literature review is focused on primary sources for answering research questions. However, for better comprehensiveness in addressing RQ3 “What are the metrics used to evaluate sustainability in data centers?” specifically, broadening the scope to include data center subsystems' metrics as well as secondary sources such as formally-published systematic literature reviews focused on data center metrics may have been more appropriate. However, given the aim to explore and form an overview on how data center sustainability is evaluated and measured, conducting the MLR using primary sources was deemed sufficient for the scope of this study.

Although a range of sustainability dimensions, metrics, tools, and methodologies for evaluating data center sustainability were identified, the findings should be viewed as indicative rather than exhaustive. This is in part due to the specificity of the search queries, which narrowed the search space and may have affected the comprehensiveness of this review. For example, inclusion and exclusion criteria such as I1 (include sources focused on facility-level sustainability evaluation, covering dimensions, tools, or metrics), I3 (formal literature: include empirical studies using experiments, case studies, surveys, and real-world data), I4 (gray literature: For RQ1 and RQ3, sources of high and moderate credibility were included, whereas lower credibility sources was accepted for RQ2), and E5 (gray literature: source has to be in PDF format) presented in Section 3.5 may have excluded potentially relevant papers and constrained the diversity and novelty of the results across all research questions. Ultimately, to maintain credibility and ensure the inclusion of high-quality sources, it was necessary to restrict the search space.

The metrics, tools, methodologies, and representative terms identified for RQ1 (Table 4.1) can be simultaneously associated with multiple sustainability dimensions. Thus, the findings presented in Table 4.1 and Table 4.3 can be classified in various ways. For example, Power Usage Effectiveness (PUE) can be interpreted as a technical or environmental metric, while security can be considered to be related to both technical and social dimensions. Furthermore, there were differences in the reviewed literature in the way that carbon dioxide emissions were perceived. For example, they were associated with social (FL1, FL2 and FL4), economic (FL4, FL9), and environmental impacts (e.g., FL9 and FL12). In an attempt to address ambiguity, the findings were classified according to the established definition of sustainability dimensions from a data center perspective in Subsection 2.2. However, sustainability is a broad and interpretive concept, and such classifications are inherently subjective to some extent.

5.3 Future work

Based on the findings of this thesis, future research should focus on several areas. For example, the holistic evaluation of data centers appears to still be a relatively new concept, despite the growing recognition of the need to focus on sustainability more broadly than just from the perspective of energy. This raises the question of whether there are specific challenges or obstacles concerning holistic evaluation and what exactly are they. In addition, the challenges of applying metrics in practice should be further investigated. For example, although there are several metrics, it was found that Power Usage Effectiveness (PUE) was by far the most commonly referenced metric in the final selection of sources. Understanding why other metrics are less commonly used or reported due to complexity, lack of standardization, or other reasons could provide valuable information to improve metrics.

Future research should also focus on the development of novel tools and methodologies for the holistic evaluation of data center sustainability, as there appears to be a lack of comprehensive tools and frameworks that can fully integrate and balance the various sustainability dimensions and metrics required for a thorough evaluation. The development of such systems could better capture the complex and interconnected nature of data center sustainability and support data centers in meeting sustainability goals and reporting requirements.

Future work should also explore whether the use of sustainability metrics, tools, and methodologies varies depending on the attributes of a data center, such as type, location, or size, and how it may differ. This could help identify potential gaps in the way different dimensions of sustainability are evaluated or how metrics, methodologies, and tools are used in data centers, and improve industry-wide benchmarking and transparency.

6 Summary

The aim of this thesis was to explore how data center sustainability is evaluated and measured. To identify the metrics, methodologies, and tools used and the sustainability dimensions addressed in data center sustainability evaluations, a multivocal literature review was conducted in order to capture knowledge both from practice and formally-published literature. For formal literature searches, four scientific databases were chosen, whereas the Google search engine was chosen for the search for gray literature. Inclusion and exclusion criteria were applied to identify relevant sources, resulting in a final pool of thirty-three sources that were published during the years 2010–2025.

The findings show that data center sustainability is evaluated by use of various metrics, tools, and methodologies, which alludes to fragmented evaluation practices in the data center industry. Although data center sustainability was found to be evaluated across all the sustainability dimensions, the primary focus is on the operational stage and environmental sustainability through energy efficiency in particular. However, there are also some efforts to evaluate sustainability more comprehensively by considering the different stages of the data center life cycle and a wider range of factors, such as carbon emissions, water usage, electronic waste, and community impacts.

Future research should focus on a holistic evaluation of data center sustainability and the development of comprehensive tools and methodologies that can fully integrate and balance the various sustainability dimensions and metrics required for a thorough evaluation.

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Appendix A Search Strings

A.1 Gray Literature Search Strings

```
1: filetype:pdf sustainability report ("data center" OR "datacenter" OR "data
centre" OR "datacentre")

2: sustainability evaluation tool ("data center" OR "datacenter" OR "data centre"
OR "datacentre") filetype:pdf
```

A.2 Formal Literature Search Strings

A.2.1 Scopus

```
( TITLE-ABS-KEY ( ( sustainab* OR eco-friend* OR green* ) AND ( metric* OR indicator* OR
measurement* OR "criteria" ) AND ( "energy" OR "power" OR "efficiency" OR "consumption" OR "usage"
) AND ( "performance" OR "assessment" OR "evaluation" OR "analysis" ) AND ( "experiment" OR "case
study" OR "interview" OR "questionnaire" ) ) AND TITLE ( "data center" OR "datacenter" OR "data
centre" OR "datacentre" OR "data centers" OR "datacenters" OR "data centres" OR "datacentres" ) )
OR ( TITLE-ABS-KEY ( ( sustainab* OR eco-friend* OR green* ) AND ( metric* OR indicator* OR
measurement* OR "criteria" ) AND ( "carbon" OR "GHG" OR "green house gas" OR "greenhouse gas" OR
emission* OR "waste" OR "e-waste" OR "electronic waste" OR "recycling" OR "water" OR "cooling" OR
"waste-heat" OR "waste heat" OR "waste heat utilization" OR "heat recovery" ) AND ( "performance"
OR "assessment" OR "evaluation" OR "analysis" ) AND ( "experiment" OR "case study" OR "interview"
OR "questionnaire" ) ) AND TITLE ( "data center" OR "datacenter" OR "data centre" OR "datacentre"
OR "data centers" OR "datacenters" OR "data centres" OR "datacentres" ) ) OR ( TITLE-ABS-KEY ( (
sustainab* OR eco-friend* OR green* ) AND ( "evaluation" OR "assessment" OR "analysis" OR
"measurement" ) AND ( "methodology" OR "framework" OR "approach" OR "technique" OR "method" ) AND
( "tool" OR "instrument" ) AND ( "experiment" OR "case study" OR "interview" OR "questionnaire" )
) AND TITLE ( "data center" OR "datacenter" OR "data centre" OR "datacentre" OR "data centers" OR
"datacenters" OR "data centres" OR "datacentres" ) ) OR ( TITLE-ABS-KEY ( ( sustainab* OR
eco-friend* OR green* ) AND ( "impact" OR "consequence" OR "health" OR "education" OR "well-being"
) AND ( "individual" OR "personal" OR user* OR *stakeholder* OR employee* OR practitioner* ) AND (
"experiment" OR "case study" OR "interview" OR "questionnaire" ) ) AND TITLE ( "data center" OR
"datacenter" OR "data centre" OR "datacentre" OR "data centers" OR "datacenters" OR "data centres"
OR "datacentres" ) ) OR ( TITLE-ABS-KEY ( ( sustainab* OR eco-friend* OR green* ) AND ( "cost
reduction" OR "operational efficiency" OR "financial performance" OR "profitability" OR "economic
performance" OR cost-effectiv* OR "return on investment" OR "ROI" ) AND ( "experiment" OR "case
study" OR "interview" OR "questionnaire" ) ) AND TITLE ( "data center" OR "datacenter" OR "data
centre" OR "datacentre" OR "data centers" OR "datacenters" OR "data centres" OR "datacentres" ) )
OR ( ( TITLE-ABS-KEY ( ( sustainab* OR eco-friend* OR green* ) AND ( "impact" OR "consequence" )
AND ( "community" OR "communities" OR "social" ) ) AND TITLE ( "data center" OR "datacenter" OR
"data centre" OR "datacentre" OR "data centers" OR "datacenters" OR "data centres" OR
"datacentres" AND ( "experiment" OR "case study" OR "interview" OR "questionnaire" ) ) ) ) AND (
LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "cp" ) ) AND ( LIMIT-TO ( LANGUAGE , "English"
) )
```

A.2.2 Web of Science

The combined query below was used for search.

```
6 OR 5 OR 4 OR 3 OR 2 OR 1 and English (Languages) and Article or Proceeding Paper (Document
Types) and English (Languages)
```

```
1: TS=((sustainab* OR eco-friend* OR green*) AND ("impact" OR "consequence") AND ("community" OR
"communities" OR "social") AND ("experiment" OR "case study" OR "interview" OR "questionnaire"))
AND TI=("data center" OR "datacenter" OR "data centre" OR "datacentre" OR "data centers" OR
"datacenters" OR "data centres" OR "datacentres")
```

```
2: TS=((sustainab* OR eco-friend* OR green*) AND ("cost reduction" OR "operational efficiency"
OR "financial performance" OR "profitability" OR "economic performance" OR cost-effectiv* OR
"return on investment" OR ROI) AND ("experiment" OR "case study" OR "interview" OR
"questionnaire")) AND TI=("data center" OR "datacenter" OR "data centre" OR "datacentre" OR "data
centers" OR "datacenters" OR "data centres" OR "datacentres") )
```

```
3: TS=((sustainab* OR eco-friend* OR green*) AND ("impact" OR "consequence" OR "health" OR
"education" OR "well-being") AND ("individual" OR "personal" OR user* OR *stakeholder* OR
employee* OR practitioner*) AND ("experiment" OR "case study" OR "interview" OR "questionnaire"))
AND TI=("data center" OR "datacenter" OR "data centre" OR "datacentre" OR "data centers" OR
"datacenters" OR "data centres" OR "datacentres")
```

```
4: TS=((sustainab* OR eco-friend* OR green*) AND ("evaluation" OR "assessment" OR "analysis" OR
"measurement") AND ("methodology" OR "framework" OR "approach" OR "technique" OR "method") AND
("tool" OR "instrument") AND ("experiment" OR "case study" OR "interview" OR "questionnaire")) AND
TI=("data center" OR "datacenter" OR "data centre" OR "datacentre" OR "data centers" OR
"datacenters" OR "data centres" OR "datacentres")
```

```
5: TS=((sustainab* OR eco-friend* OR green*) AND (metric* OR indicator* OR measurement* OR
"criteria") AND ("energy" OR "power" OR "efficiency" OR "consumption" OR "usage") AND
("performance" OR "assessment" OR "evaluation" OR "analysis") AND ("experiment" OR "case study" OR
"interview" OR "questionnaire")) AND TI=("data center" OR "datacenter" OR "data centre" OR
"datacentre" OR "data centers" OR "datacenters" OR "data centres" OR "datacentres")
```

```
6: TS=((sustainab* OR eco-friend* OR green*) AND (metric* OR indicator* OR measurement* OR
"criteria") AND ("carbon" OR "GHG" OR "green house gas" OR "greenhouse gas" OR emission* OR
"waste" OR "e-waste" OR "electronic waste" OR "recycling" OR "water" OR "cooling" OR "waste-heat"
OR "waste heat" OR "waste heat utilization" OR "heat recovery") AND ("performance" OR "assessment"
OR "evaluation" OR "analysis") AND ("experiment" OR "case study" OR "interview" OR
"questionnaire")) AND TI=("data center" OR "datacenter" OR "data centre" OR "datacentre" OR "data
centers" OR "datacenters" OR "data centres" OR "datacentres")
```

A.2.3 IEEE Xplore

1: (((sustainab* OR eco-friend* OR green*) AND (metric* OR indicator* OR measurement* OR "criteria") AND ("energy" OR "power" OR "efficiency" OR "consumption" OR "usage") AND ("performance" OR "assessment" OR "evaluation" OR "analysis") AND ("experiment" OR "case study" OR "interview" OR "questionnaire")) AND ("Document Title":"data center" OR "Document Title":"datacenter" OR "Document Title":"data centre" OR "Document Title":"datacentre" OR "Document Title":"data centers" OR "Document Title":"datacenters" OR "Document Title":"data centres" OR "Document Title":"datacentres"))

2: (((sustainab* OR eco-friend* OR green*) AND (metric* OR indicator* OR measurement* OR "criteria") AND ("energy" OR "power" OR "efficiency" OR "consumption" OR "usage") AND ("performance" OR "assessment" OR "evaluation" OR "analysis") AND ("experiment" OR "case study" OR "interview" OR "questionnaire")) AND ("Document Title":"data center" OR "Document Title":"datacenter" OR "Document Title":"data centre" OR "Document Title":"datacentre" OR "Document Title":"data centers" OR "Document Title":"datacenters" OR "Document Title":"data centres" OR "Document Title":"datacentres"))

3: (((sustainab* OR eco-friend* OR green*) AND ("evaluation" OR "assessment" OR "analysis" OR "measurement") AND ("methodology" OR "framework" OR "approach" OR "technique" OR "method") AND ("tool" OR "instrument") AND ("experiment" OR "case study" OR "interview" OR "questionnaire")) AND ("Document Title":"data center" OR "Document Title":"datacenter" OR "Document Title":"data centre" OR "Document Title":"datacentre" OR "Document Title":"data centers" OR "Document Title":"datacenters" OR "Document Title":"data centres" OR "Document Title":"datacentres"))

4: (((sustainab* OR eco-friend* OR green*) AND ("impact" OR "consequence" OR "health" OR "education" OR "well-being") AND ("individual" OR "personal" OR user* OR *stakeholder* OR employee* OR practitioner*) AND ("experiment" OR "case study" OR "interview" OR "questionnaire")) AND ("Document Title":"data center" OR "Document Title":"datacenter" OR "Document Title":"data centre" OR "Document Title":"datacentre" OR "Document Title":"data centers" OR "Document Title":"datacenters" OR "Document Title":"data centres" OR "Document Title":"datacentres"))

5: (((sustainab* OR eco-friend* OR green*) AND ("cost reduction" OR "operational efficiency" OR "financial performance" OR "profitability" OR "economic performance" OR cost-effectiv* OR "return on investment" OR "ROI") AND ("experiment" OR "case study" OR "interview" OR "questionnaire")) AND ("Document Title":"data center" OR "Document Title":"datacenter" OR "Document Title":"data centre" OR "Document Title":"datacentre" OR "Document Title":"data centers" OR "Document Title":"datacenters" OR "Document Title":"data centres" OR "Document Title":"datacentres"))

6: (((sustainab* OR eco-friend* OR green*) AND ("impact" OR "consequence") AND ("community" OR "communities" OR "social")) AND ("Document Title":"data center" OR "Document Title":"datacenter" OR "Document Title":"data centre" OR "Document Title":"datacentre" OR "Document Title":"data centers" OR "Document Title":"datacenters" OR "Document Title":"data centres" OR "Document Title":"datacentres") AND ("experiment" OR "case study" OR "interview" OR "questionnaire"))

A.2.4 ACM Digital Library

In addition to the search query below, the content type filter was set to “Research Articles”.

```
( (Title:("data center" OR datacenter OR "data centre" OR datacentre OR "data centers" OR
datacenters OR "data centres" OR datacentres) AND (Abstract:(sustainab* OR eco-friend* OR green*)
AND (metric* OR indicator* OR measurement* OR "criteria") AND ("energy" OR "power" OR "efficiency"
OR "consumption" OR "usage") AND ("performance" OR "assessment" OR "evaluation" OR "analysis") AND
("experiment" OR "case study" OR "interview" OR "questionnaire"))) ) OR ( (Title:("data center" OR
datacenter OR "data centre" OR datacentre OR "data centers" OR datacenters OR "data centres" OR
datacentres) AND (Abstract:(sustainab* OR eco-friend* OR green*) AND (metric* OR indicator* OR
measurement* OR "criteria") AND ("carbon" OR "GHG" OR "green house gas" OR "greenhouse gas" OR
emission* OR "waste" OR "e-waste" OR "electronic waste" OR "recycling" OR "water" OR "cooling" OR
"waste-heat" OR "waste heat" OR "waste heat utilization" OR "heat recovery") AND ("performance" OR
"assessment" OR "evaluation" OR "analysis") AND ("experiment" OR "case study" OR "interview" OR
"questionnaire"))) ) OR ( (Title:("data center" OR datacenter OR "data centre" OR datacentre OR
"data centers" OR datacenters OR "data centres" OR datacentres) AND (Abstract:(sustainab* OR
eco-friend* OR green*) AND ("evaluation" OR "assessment" OR "analysis" OR "measurement") AND
("methodology" OR "framework" OR "approach" OR "technique" OR "method") AND ("tool" OR
"instrument") AND ("experiment" OR "case study" OR "interview" OR "questionnaire"))) ) OR (
(Title:("data center" OR datacenter OR "data centre" OR datacentre OR "data centers" OR
datacenters OR "data centres" OR datacentres) AND (Abstract:(sustainab* OR eco-friend* OR green*)
AND ("impact" OR "consequence" OR "health" OR "education" OR "well-being") AND ("individual" OR
"personal" OR user* OR *stakeholder* OR employee* OR practitioner*) AND ("experiment" OR "case
study" OR "interview" OR "questionnaire"))) ) OR ( (Title:("data center" OR datacenter OR "data
centre" OR datacentre OR "data centers" OR datacenters OR "data centres" OR datacentres) AND
(Abstract:(sustainab* OR eco-friend* OR green*) AND ("cost reduction" OR "operational efficiency"
OR "financial performance" OR "profitability" OR "economic performance" OR cost-effectiv* OR
"return on investment" OR "ROI") AND ("experiment" OR "case study" OR "interview" OR
"questionnaire"))) ) OR ( (Title:("data center" OR datacenter OR "data centre" OR datacentre OR
"data centers" OR datacenters OR "data centres" OR datacentres) AND (Abstract:(sustainab* OR
eco-friend* OR green*) AND ("impact" OR "consequence") AND ("community" OR "communities" OR
"social")) AND (ALL:("experiment" OR "case study" OR "interview" OR "questionnaire"))) )
```

Appendix B Selected Sources

Table B.1: Selected sources ordered by source category (gray or formal literature) and alphabetically by title.

ID	Year	Author(s)	Title	Source type
GL1	2024	EdgeConneX	2023 Sustainability Report	Sustainability report
GL2	2021	BEAM and HKGBC	BEAM Plus Data Centres Assessment Tool Advocates Sustainable Development	Press release
GL3	2020	Herrlin, Magnus	Data Center Energy Assessment Process Manual	Process manual
GL4	2024	The Open Compute Project (OCP)	Data Center Facility Sustainability Metrics	White paper
GL5	2023	McDonald, Rosie and Ballan, Sara.	Green data centers: towards a sustainable digital transformation	Practitioner's guide
GL6	2023	Lin, Paul and Bunger, Rober and Avelar, Victor	Quantifying Data Center Scope 3 GHG Emissions to Prioritize Reduction Efforts	White paper
GL7	2024	CDC	Sustainability Report 2024	Sustainability report
GL8	2010	The U.S. Department of Energy	The Data Center Energy Profiler (DC Pro) Software Tool Suite	Technical brochure
GL9	2024	NextDC	Unlocking Excellence for Sustainability	Evaluation checklist

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Table B.1 – Continued from the previous page

ID	Year	Author(s)	Title	Source type
FL1	2018	Anthony, Bokolo and Abdul Majid, Mazlina and Romli, Awanis	A collaborative agent based green IS practice assessment tool for environmental sustainability attainment in enterprise data centers	Article
FL2	2018	Anthony, Bokolo and Abdul Majid, Mazlina and Romli, Awanis	A Descriptive Study towards Green Computing Practice Application for Data Centers in IT Based Industries	Conference paper
FL3	2020	Li, Jian and Jurasz, Jakub and Li, Hailong and Tao, Wen-Quan and Duan, Yuanyuan and Yan, Jinyue	A new indicator for a fair comparison on the energy performance of data centers	Article
FL4	2010	Pendelberry, Sidney L. and Su, Sophie Ying Chen and Thurston, Michael	A Taguchi-based method for assessing data center sustainability	Conference paper

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Table B.1 – Continued from the previous page

ID	Year	Author(s)	Title	Source type
FL5	2022	Samuel, Patrick Katuta and Moses, Peter Musau and Davies, Segera and Wekesa, Cyrus	Analysis of Energy Utilization Metrics as a Measure of Energy Efficiency in Data Centres: Case Study of Wananchi Group (Kenya) Limited Data Centre	Conference paper
FL6	2016	Pegus, Patrick and Varghese, Benoy and Guo, Tian and Irwin, David and Shenoy, Prashant and Mahanti, Anirban and Culbert, James and Goodhue, John and Hill, Chris	Analyzing the Efficiency of a Green University Data Center	Conference paper
FL7	2021	Lam, Patrick T.I. and Lai, Daniel and Leung, Chi-Kin and Yang, Wenjing	Data centers as the backbone of smart cities: principal considerations for the study of facility costs and benefits	Article
FL8	2013	Flucker, Sophia and Tozer, Robert	Data centre energy efficiency analysis to minimize total cost of ownership	Article

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Table B.1 – Continued from the previous page

ID	Year	Author(s)	Title	Source type
FL9	2016	Isidori, Daniela and Standardi, Laura and Manca, Massimiliano and Cristalli, Cristina	Efficient monitoring system for Data Center: Agorà case study	Conference paper
FL10	2023	Gao, Jianyong and Li, Fangjun and Wang, Jing and Wang, Qiong and Jia, Najuan	Energy Efficiency and Green Computing in Large-scale Data Centers	Conference paper
FL11	2011	Lu, Xiaoshu and Lu, Tao and Remes, Matias and Viljanen, Martti	Energy Efficiency Assessment for Data Center in Finland: Case Study	Conference paper
FL12	2024	Jerléus, Kim and Ibrahim, Muhammad Asim and Augustsson, Anna	Environmental footprints of the data center service sector in Sweden	Article
FL13	2021	Zhang, Qingyu and Yang, Shimiao	Evaluating the sustainability of big data centers using the analytic network process and fuzzy TOPSIS	Article

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Table B.1 – Continued from the previous page

ID	**Year**	**Author(s)**	**Title**	**Source type**
FL14	2017	Guyon, David and Orgerie, Anne-Cécile and Morin, Christine	GLENDA: Green Label towards Energy proportioNality for IaaS DAta centers	Conference paper
FL15	2012	Sego, Landon H. and Márquez, Andrés and Rawson, Andrew and Cader, Tahir and Fox, Kevin and Gustafson, William I. and Mundy, Christopher J.	Implementing the data center energy productivity metric	Article
FL16	2013	Lu, Tao and Lu, Xiaoshu and Viljanen, Martti	Investigation of sustainable cooling strategy for data center	Conference paper
FL17	2025	Samaye, Ismael and Ouffoué, Georges and Gamatié, Abdoulaye	Life Cycle Assessment of Edge Data Centers: Case Study in Presence of Renewable Energy and Refurbished Servers	Article

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Table B.1 – Continued from the previous page

ID	**Year**	**Author(s)**	**Title**	**Source type**
FL18	2022	Sovacool, Benjamin K. and Monyei, Chukwuka G. and Upham, Paul	Making the internet globally sustainable: Technical and policy options for improved energy management, governance and community acceptance of Nordic datacenters	Article
FL19	2020	Shaikh, Asadullah and Uddin, Mueen and Elmagzoub, Mohamed A. and Alghamdi, Abdullah	PEMC: Power Efficiency Measurement Calculator to Compute Power Efficiency and CO_2 Emissions in Cloud Data Centers	Article
FL20	2011	Smith, Alan D.	Strategic sustainability and operational efficiency dilemma of data centres	Article
FL21	2022	Sovacool, Benjamin K. and Upham, Paul and Monyei, Chukwuka G.	The “whole systems” energy sustainability of digitalization: Humanizing the community risks and benefits of Nordic datacenter development	Article
FL22	2015	Whitehead, Beth and Andrews, Deborah and Shah, Amip	The life cycle assessment of a UK data centre	Article

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Table B.1 – Continued from the previous page

ID	**Year**	**Author(s)**	**Title**	**Source type**
FL23	2014	Seegolam, Ashwin and Usmani, Kaleem Ahmed	Understanding the maturity of EU code of conduct on data centres: A Mauritian case study explained	Conference paper
FL24	2022	Karimi, Leila and Yacuel, Leeann and Johnson, Joseph Degraft and Ashby, Jamie and Green, Michael and Renner, Matt and Bergman, Aryn and Norwood, Robert and Hickenbottom, Kerri L.	Water-energy tradeoffs in data centers: A case study in hot-arid climates	Article

Appendix C Quality scores for gray literature

Table C.1: Gray literature quality assessment.

Criterion	GL1	GL2	GL3	GL4	GL5	GL6	GL7	GL8	GL9
Q1	1	1	1	1	1	1	1	1	1
Q2	0	0	1	1	1	1	0	0	0
Q3	0	0	1	1	0	1	0	0	0
Q4	0	0	1	1	1	1	0	0	0
Q5	1	0	1	1	0	1	1	1	0
Q6	1	0	0	0	0	1	1	0	0
Q7	1	1	1	1	1	1	0	1	0
Q8	1	0	0	1	0	0	1	0	1
Q9	1	1	1	1	1	1	1	1	1
Q10	1	1	1	1	1	1	1	1	1
Q11	1	0	0	1	1	1	1	0	0
Q12	1	1	1	1	1	1	1	0	0
Q13	1	0	1	1	1	1	1	0	0
Q14	1	0	1	1	1	1	1	0	0
Q15	1	1	1	1	1	1	1	0	1
Q16	1	1	1	1	1	1	0	1	0
Q17	1	1	1	1	1	1	1	1	1
Q18	0,5	0,5	1	1	1	1	0,5	0	0
Sum (out of 18)	14,5	8,5	15	17	14	17	12,5	7	6
Normalized (0–1)	0,81	0,47	0,83	0,94	0,78	0,94	0,69	0,39	0,33

Appendix D Quality scores for formal literature

Table D.1: Formal literature quality assessment.

Source	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Total
FL1	1	1	1	1	1	1	1	7
FL2	1	1	1	1	0,5	0,5	0,5	5,5
FL3	1	1	1	1	1	1	1	7
FL4	0,5	1	1	1	1	0	1	5,5
FL5	1	1	1	0,5	1	0	1	5,5
FL6	1	1	1	1	1	0	1	6
FL7	1	1	1	1	1	0,5	1	6,5
FL8	1	1	0,5	1	1	0	1	5,5
FL9	1	1	1	0,5	1	0	1	5,5
FL10	1	1	1	1	1	0,5	1	6,5
FL11	1	1	1	1	1	0	0,5	5,5
FL12	1	1	1	1	1	1	1	7
FL13	1	1	1	1	1	0	1	6
FL14	1	1	1	1	1	0	1	6
FL15	0,5	1	1	1	1	1	1	6,5
FL16	1	1	1	1	1	0	0,5	5,5
FL17	1	0,5	0,5	1	1	1	1	6
FL18	0,5	1	1	1	1	0	1	5,5
FL19	0,5	0,5	0,5	1	1	0	1	4,5
FL20	1	1	1	1	1	0	1	6
FL21	1	1	1	1	1	0	1	6
FL22	1	1	1	1	1	0	1	6
FL23	1	0,5	0,5	1	1	1	1	6
FL24	1	1	1	1	1	0	1	6