Research Article

Investigating the Environmental Sustainability of Data Centers

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ABSTRACT

Data centers play a critical role in supporting global IT infrastructure, representing a rapidly growing industry. However, this growth is coupled with significant environmental consequences, such as the consumption of 1-2% of the annual global energy supply, increased carbon emissions, and the loss of valuable agricultural land. This study reviews solutions that address these impacts by evaluating sustainable practices in data center construction, design, and maintenance. The results point to several key strategies that improve environmental sustainability in these categories. In construction, replacing traditional materials, such as concrete and steel, with eco-friendly alternatives such as green concrete and steel slag can reduce carbon footprints. Additionally, permeable pavements can manage the stormwater runoff that was previously absorbed by the farmland on which data centers are built. Design improvements, including underfloor air distribution, economizers, ice storage, and energy recovery wheels can optimize ventilation systems, lowering energy demands by up to 25%. Sustainable maintenance practices emphasize the use of advanced liquid cooling systems, as well as thermal energy storage to reduce peak electricity usage and incorporate more renewable energy sources. Overall, it is vital to implement strategies that prioritize sustainability in data centers in relation to the construction, design, and maintenance to reduce the environmental footprint of this growing industry.

Keywords: Sustainability; Circulation; Constructing Data Centers; Data Center Design; Operating Data Centers

INTRODUCTION

As the digital world continues to grow, the prominence of data centers only increases, with the environmental costs of these centers growing alongside it. This review highlights the need for solutions to promote sustainable practices in data centers, related to design, construction, and maintenance. The goal of this study is to determine how current environmental harm can be mitigated in existing data centers to maximize sustainability in future data centers.

Data centers are crucial, as they store integral IT infrastructure such as servers, computing machines, and other tech-related equipment. They centralize and store data for companies. The demand for data centers has only increased, with the number of data centers boosting exponentially in the past couple of years (10). There are more than 10,500 data centers worldwide and the industry is expected to grow by more than 11% each year, propelling the worth of the data center market to an

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expected 775 billion dollars by 2029 (15).

However, these data centers come with a significant environmental impact. In short, they use approximately 200 terawatt hours (TWh) of energy per year, which is greater than some countries. In other words, they consume 1-2% of global power annually. The carbon emissions and power consumption of data centers are expected to more than double by 2030 (4).

These environmental challenges make ensuring sustainable practices in data centers even more important, especially when considering the fact that climate change is a progressing problem. This report will evaluate the practices of data centers throughout their entire life cycle, to determine strategies that best minimize the environmental cost.

Background

Data centers have been around for 80 years, when the first data center was built to house a digital computer, called the ENIAC, in 1945. In the 1960s, data centers, or computer rooms, were built in office buildings, with faster and more powerful mainframes. As computers got smaller, data centers adapted, with minimal concern about environmental conditions. In the 1990s, the .com boom drove the construction of even larger data centers with thousands of servers. By the 2000s, many organizations incorporated cloud services, which only increased the demand for data centers as facilities were needed to manage these services (17).

This paper focuses on data centers in the context of the environment. In order to discuss the environment, environmental sustainability must be understood. However, the topic of environmental sustainability is broad, which is why it is vital that the most relevant factors are prioritized throughout the lifecycle of data centers.

Construction. Data centers have to house computer systems, storage, and other IT equipment, making it essential for them to be durable. They are typically made of steel or concrete, or a combination of both. Concrete is widely used in data centers due to its durability, protecting equipment from environmental hazards. It can also help regulate the temperature of the facility, which is crucial for buildings that host thousands of servers that overheat easily (24). Steel is also used in data centers because it can support the weight of thousands of servers. Additionally, building the original structure out of steel makes expansion easier in the future, limiting the cost to expand. It also increases the airflow potential in the large open spaces inside data centers (21). However, the production of these materials can be quite damaging to the environment.

In fact, during the construction process, concrete can represent up to 80% of carbon emissions. While it is important to understand that this percentage varies for each data center, concrete is still a vital part of the construction process. This is a problem because making concrete is an energy intensive process. Each pound of concrete emits nearly a pound of carbon dioxide (16). Additionally, steel production requires large amounts of coal, an element that has to be drilled out of the ground. In fact, the production of steel emits the most carbon dioxide out of any other activity yearly.

Data centers are often constructed on important agricultural land (22). Farmland is vital in many different ways, as it helps combat climate change and its effects. For instance, it filters and absorbs stormwater, preventing the massive runoff of polluted water into local bodies of water. However, when data centers occupy this land, the agricultural benefits are limited. One example of a hub of data centers is the Northern Virginia DC area. As shown in Figure 1, Virginia is undergoing millions of square feet of data center development. Loudoun County, a prominent county in Northern Virginia, leads with more than 30 million square feet being built (8). This example can provide more context on where data centers are built in a community.

Design. Second, the design of data centers can have a large impact on its environmental sustainability. In order to discuss design strategies, it is important to understand that certain considerations must be made in order for these data centers to serve their purpose. For instance, the data center must be large enough to hold all the IT infrastructure and must have room to expand. Most contractors look for a site that is affordable. They also

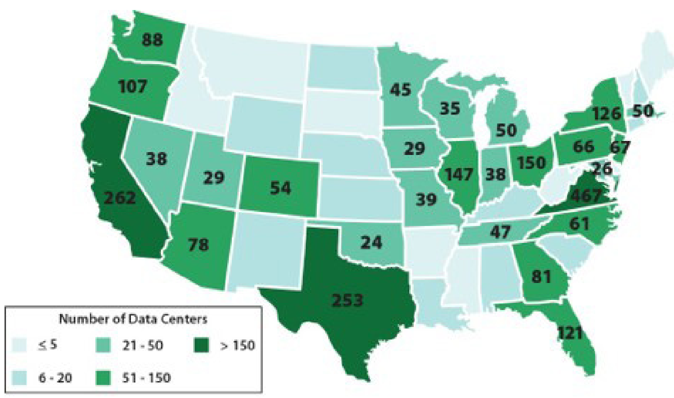

Figure 1. 2024 Map of the United States relative to the number of data centers (Slagowski and DesAutels).

look for a site that is easily accessible, ensuring reliable telecommunication and low-cost energy.

Additionally, it is important to consider the types of infrastructure that must be present inside data centers. For example, hundreds of servers, cables, racks, and management platforms must be present. Therefore, the design of the outside and inside of the data center must be structured in a manner to accommodate these technologies. For example, data center designers have to avoid the mixing of hot and cold air to maximize the effectiveness of the cooling systems. All of these considerations affect the decisions that data center manufacturers make. Currently, data centers appear long and flat, as this is the cheapest alternative for data center manufacturers.

Maintenance. Lastly, maintaining data centers can have a notable environmental impact due to the large number of servers they house. Furthermore, data centers have technology that is constantly in operations. Since the technology is always computing, technology could overheat, malfunction, or even break down. That's why many data centers utilize water-based cooling systems to bring this equipment back down to room temperature. One example of a water-based cooling system is cooling towers that spray water onto a heat surface to cool the air down. This air will then be filtered into the data center (3). Although water-based cooling systems come in various forms, they generally require significant amounts of water.

Moreover, data centers require signifcant power to run. In fact, a large data center can consume up to 100 megawatts of power, which is the same amount of power required for roughly 80,000 homes. Most companies also look for power that is electrically clean, free of disruptions, and is as inexpensive as possible (19). However, meeting power demands can be challenging, especially because every day, the power demand varies, since the amount of work the servers are doing changes every day. This is a problem because to supply for this changing power demand, data center manufacturers source their energy from fossil fuels. In fact, the global data center industry is expected to emit 2.5 billion tons of carbon dioxide in the next couple of years (9). Unfortunately, the energy consumption of these data centers is only increasing with the addition of artificial intelligence and cloud computing technologies.

Overall, data centers have a negative environmental impact throughout the construction, design, and maintenance phases of its lifecycle. Although there has been an increased push for manufacturers to convert to more sustainable practices, manufacturers often prioritize efficiency over environmental sustainability. While efficiency is undoubtedly important, it is also vital to focus on environmental sustainability in the context of these data centers. Environmental sustainability is required to preserve the world for present and future generations. This will be explored in this study.

METHODS

To conduct this literature review, several databases were searched, including **JSTOR**, **Google Scholar,** and **ScienceDirect.** The purpose of the search was to identify relevant published studies from reputable journals that discussed data center sustainability in relation to construction and maintenance of these data centers. Keywords used included: "**pue of data centers", "eco-friendly data centers", "constructing data centers",** and **"IT for data centers".** These keywords were used in combination with each other.

Studies were included if they were published in peer-reviewed journals that were known to be reliable. Additionally, if the studies were written in English and published between 2008 and 2024, they were also included. Lastly, if the studies focused on the design, construction, or maintenance (energy/cooling) of data centers and provided either new solutions or theoretical frameworks, they were included.

For each of the selected studies, the following was extracted: author citation, publication date, study design, key findings, proposed solutions, and relevance to the research question. The data was then synthesized utilizing visual thematic analysis, in the form of organized tables. Studies were grouped based on the chosen sustainability factors. This allowed for simple comparative analysis to identify patterns and gaps in the literature.

Some limitations of this literature review were the quality, availability, and type of sources. For instance, selected sources had to be peer-reviewed and published in a reputable journal. The sources found were also limited based on when they were published, where only articles published between 2008 and 2024 were accepted. This limited the quantity of sources available on the topic. Additionally, it is important to note that there were significantly more sources on the topic of maintenance than on construction, simply because there are more strategies that exist related to the maintenance of data centers. To expand, since data center maintenance relates directly to the economic costs of data center energy consumption, much research on data centers focuses on maintenance strategies that can reduce the economic costs for these manufacturers. This means that there are less articles available on specific construction and design strategies relating to data centers.

Data centers were also researched in context of their location within a community. This research was not in the form of studies but rather in the form of news reports, which talk about where these data centers are located. Some suggestions were made based on the Northern Virginia DC area, to provide further discussion on the adaptations that data center strategies can incorporate in different areas.

RESULTS

In the results section, the reviewed literature will be categorized, classified, and organized in order to provide enough information to create a comprehensive strategy for data center sustainability. Table 1 contains a general overview of the sources reviewed, identifying the proposed solution, relevance to this study, limitations, and key findings.

As Table 1 depicts, strategies tackle a variety of

Table 1. Findings of the reviewed sources

Author(s)	Publication Date	Relevance to Paper	Key Findings	Proposed Solution	Limitations
Zhu et al. (26)	February 2023	Maintenance Energy	The analysis talks about optimization techniques with a goal of reducing energy consumption about 20–40%. These techniques specifically target streamlining IT equipment and cooling technology.	The proposed solution includes the usage of Power Purchase Agreements to source renewable energy, innovative cooling techniques, and waste recovery systems.	This study does not consider geographic differences or the incentives of firms to convert to low-carbon (no financial discussion).
Guo et al. (5)	November 2021	Maintenance Power Grid and Sourcing Location	This analysis talks about how data centers can utilize smarter energy systems to minimize economic harms. It discusses how stakeholders typically make decisions regarding where to place data centers.	This proposed solution is smart grid technology that can optimize consumption of energy.	This study focuses on how to negotiate between the grid suppliers and the data center to minimize costs, not necessarily to reduce environmental harms.
Oro et al. (11)	June 2015	Maintenance Cooling	The analysis talks about TES, thermal energy storage, which will be charged by cold water from the chiller.	This proposed solution provides cold energy for 15 minutes and the annual electrical cost by 3%.	The paper's results suggest that the implementation of TES to store cold energy is not recommended. It is only potentially useful in the short-term.
Hammann et al. (6)	June 2011	Maintenance Cooling	This is an analysis discussing an invention of an energy-efficient data center cooling technique utilizing solar cooling.	There are a variety of cooling techniques explained and laid out in diagrams. One includes a water loop, another is a solar cooling unit, and another is a refrigeration chiller unit.	There are no metrics on how accurate the cooling systems are, it is simply a proposal. Water has to be sourced from somewhere in the first two cooling strategies - free cooling does solve that issue.

Continued Table 1. Findings of the reviewed sources

Author(s)	Publication Date	Relevance to Paper	Key Findings	Proposed Solution	Limitations
Araya et al. (2)	June 2018	Maintenance Energy	This is an analysis of an organic rankic cycle as a possible generator of electricity that can use the excess heat from data centers	The proposed solution is an ORC (organic rankic cycle) system that serves as waste heat recovery. It then uses the heat energy to generate electricity.	The study illustrates a thermal efficiency of only 2%, which is relatively low.
Uddin et al. (25)	August 2012	Maintenance IT & Energy	This is an analysis of an energy-saving framework which discusses IT equipment optimization.	The proposed solution is a framework that aims to utilize the smallest amount of energy to process the maximum number of tasks.	The study doesn't consider the growing data center industry and the advancing technology that doesn't all rely on the same server.'
Alizadeh et al. (1)	September 2010	Maintenance Energy	The paper presents an analysis of DCTCP (Data Center TCP), a program that speeds up workloads by maximizing data center switches.	It utilizes 90% less buffer space, through the usage of ECN. It diffuses the flow of traffic without worsening performance.	The study doesn't consider the environmental harms of the program and doesn't even mention the environment.
Pan et al. (13)	August 2008	Construction Design	The goal of this study is to evaluate the energy cost savings of green building design options in relation to an R&D data center building in Shanghai. There are multiple energy efficiency strategies.	The study shows a 27% energy cost saving in one building and another 21% in another building.	The study is specific to a simulation on an R&D center in China. There are design suggestions that can be taken away from this simulation though, however, they may not all apply to data centers in the US.
Shehabi et al. (18)	May 2011	Construction Location	The goal of this study is to identify strategies that characterize local climate and mechanical equipment and evaluate their consequences for individual data centers in the US.	The study indicates that a widespread "economizer" can reduce energy demand by 25%. They push for data center development to consider site location to limit the environmental impact of gathering resources.	The study is specific to understanding the effect of where sites are located. It indicates that larger data centers are more efficient than smaller data centers but it doesn't consider the energy requirements for each of these centers - typically, large data centers require more energy,
Pierson et al. (14)	July 2019	Maintenance Energy	The goal of this study is to mitigate the fact that renewable energy is intermittent by ensuring the availability of renewable sources at all times.	The proposed solution is called DATAZERO and it utilizes multiple renewable sources of energy. It distributes power in 3 modules.	The algorithm hasn't been tuned and it relies on the cooperation of many renewable energy companies (which isn't the most reliable thing).

environmental concerns in data centers. Namely, many of the reviewed studies propose a type of power distribution system that deals with power consumption. Additionally, many reviewed studies propose cooling systems. To better visualize comparisons between studies, Table 2 was created. The following table, Table 2, summarizes the content in Table 1, discussing the specific strategies related to design, construction, and maintenance in the context of data centers.

The following table, Table 3, references the construction specific aspects of data center sustainability. It focuses on the two main materials that are utilized to create data centers, concrete and steel. It then offers alternatives to the current methods utilized.

Data centers are typically built on farmland. For example, the Red Ace Data Center in Northern Virginia was just approved, rezoning more than 60 acres of land from farmland to industrial land. This could be a concern, as farmland plays an important role in absorbing stormwater and reducing water pollution. However, permeable pavement around data centers could be the solution (18). These permeable pavements can soak up harmful infiltrates before they even have the chance to touch the river. Certain aspects of the pavement such as a geotextile layer and larger pores can increase the absorption rate too. There is a limitation though, that after six years, the pavement becomes so clogged that runoff passes over it normally.

Overall, the tables provided in this section summarize the findings, proposed solutions, and limitations of the reviewed studies, connecting the findings to the research question: How can data centers reduce their environmental footprint?

The reviewed studies present a variety of strategies that aim to reduce the environmental impact of data centers. These strategies vary in feasibility, geographical

Table 2. Summarized version of Table 1's content

Design/Construction Strategies	Maintenance Strategies
SYSTEMS IN BUILDINGS • High-efficiency building envelope (13) • Advanced lighting systems with daylight dimming (13) • Energy recovery wheel (13)	**OPTIMIZING COOLING** • Liquid cooling (fluids for heat dissipation) (26) • Free cooling (using natural resources like water and air by leveraging natural environmental conditions) (26) • Optimizing internal airflow (26) • Direct air free cooling (11) - Factoring in the outdoors + free cooling • Water loop (6) • Solar cooling (6) • Air-side free cooling (13) • Ice storage in chillers (13) • Water-cooled chillers are the most effective DX cooling systems (18)
HVAC SYSTEM • Efficient HVAC system with underfloor air distribution (13) • Routing outside air into the data center during cool weather conditions for the HVAC system (18) • Water-side economizers that utilize cooling towers to provide chilled water into the data center (18)	**POWER CONSUMPTION** • Geographical workload balancing (5) • Dynamic voltage scaling (5) • Workload temporal scheduling (5) • DCTCP program that speeds up workloads by maximizing data center switches (1) • DATAZERO, a project that can distribute different types of renewable energy through 3 modules (14)
CLIMATE • Cooler climates make energy requirements lower, making the data centers located in these areas more energy effective (18)	**THERMAL ENERGY STORAGE** • PCM or water-based storage container (11)
	WASTE HEAT RECOVERY • ORC system that recycles heat and turns it into electricity (2)

relevance, and potential environmental benefits.

For instance:

- Financial constraints are a major concern that can prevent a system from being implemented in data centers. For example, studies like Zhu *et al*. (26) emphasize the adoption of liquid cooling, which is highly efficient but requires much investment initially and much access to water resources.
- Additionally, scalability is a major concern, as even if solutions work in a small-scale environment, universal usage may be more challenging. While Guo *et al*. (5) and Pierson *et al*. (14) advocate for integrating renewable energy sources like wind and solar into data centers' energy supply, the feasibility of these solutions depend on the local energy infrastructure of the area.
- The climate and geographical conditions of a region can also change the strategies that are effective in the region. For example, Hammann *et al*.'s (6) proposal of solar cooling is more suited for regions with extreme sunlight but faces limitations in colder climates. Also, Pan *et al*.'s (13) thermal insulation strategy may be less effective in colder climates as well, such as Northern Europe.

By exploring these differences, it has become clear that a combination of strategies must be used, tailored to the specific environmental, economic, and geographical conditions of the region.

Despite the differences, some recurring strategies still emerge among studies. Namely, a large portion of the studies emphasize optimizing energy use. Techniques like dynamic power management (5) and advanced thermal

Table 3. Review of literature about alternatives to steel and concrete

Author	Related to	Summary:
Hashmi et al. (7)	Concrete	**Green concrete utilizing waste materials** 1) Fly ash concrete can be made from coal production that already occurs. This type of concrete is highly durable and compressible. The limitation is that temperatures over 400 degrees Celsius can melt the fly ash concrete. 2) Silica fume concrete can be made from furnaces containing electric arcs. This type of concrete is environmentally-friendly and can enhance the strength of the concrete by up to 20%. Silica fume concrete has the same temperature limitation. 3) It is also cheaper than cement and has been used in construction processes before. Fly ash supports sustainability because it supports a circular system by repurposing industrial waste, reducing landfill use, and decreasing the need for virgin cement production. This in turn, lowers the carbon footprint of major construction projects like data centers.
Palankar et al. (12)	Cement and concrete	1) GGBFS-FA based geopolymer binders are an alternative to Ordinary Portland Cement and can obtain high strengths and are eco-friendly. 2) Steel slag which is an industrial by-product during the manufacturing of steel can be an alternative to natural aggregates for concrete production. These materials contribute to sustainability by reducing the carbon footprint associated with cement production. Meanwhile, the demand for energy-intensive materials such as cement is also reduced.
Tangadagi et al. (23)	Steel	Steel slag is an effective eco-friendly replacement of the natural M-sand aggregate in concrete Steel slag supports sustainability by reducing the need for virgin natural aggregates, minimizing waste from steel production. It lowers the environmental impact of mining raw materials for construction as the steel from the actual production process can be re-used.

storage systems (11) are widely proposed for minimizing energy use. Additionally, cooling remains a major concern, and studies suggest liquid cooling, free cooling, and hybrid systems in order to reduce energy demands while keeping operational efficiency intact. Finally, studies go on to explain the application of eco-friendly building materials such as green concrete and steel slag, which help in significantly reducing carbon dioxide emissions during construction and provide long-term sustainability benefits (7, 23). These themes represent a multidimensional approach to reducing the environmental footprint of data centers, combining operational efficiency with sustainable design and construction practices.

DISCUSSION

Based on all the literature reviewed and the fact that the data center industry is only going to continue to grow, the best solution is to prioritize a comprehensive strategy that focuses on the sustainable construction, design, and maintenance of future data centers. Each of these aspects will help reduce the environmental implications of data centers.

Construction

To maximize environmental sustainability, eco-friendly alternatives to steel and concrete must be considered. Examples include green concrete made out of waste materials, such as fly ash or silica fume. Steel slag can also be used as an eco-friendly replacement for natural aggregates in concrete. Additionally, since data centers are typically located on crucial farmland that soaks up harmful runoff, it is important for data centers to incorporate a design that manages the additional runoff. This can be in the form of permeable pavement which can soak up stormwater runoff.

Design

Furthermore, when designing data centers, it is vital to integrate underfloor air distribution

systems, energy recovery wheels, and ice storage systems into the HVAC system to maximize energy efficiency. This will optimize temperature control and increase energy savings by streamlining the air flow in the building. Economizers can also be built to bring in outside air for cooling during colder days to minimize overall energy consumption by up to 25%.

Maintenance

The maintenance of data centers is an opportunity for technology firms to reduce their environmental footprint, while increasing the efficiency of the center. This can be done in two key ways. First, is introducing liquid cooling systems that utilize local water resources, effectively cooling down servers. Free cooling systems could be implemented, but they are less reliable in areas with colder climates. Regardless, the combination of both systems can reduce the water demand while still ensuring that there is a cooling mechanism available at all times, regardless of the temperature or outdoor air. Second, is introducing thermal energy storage, which can store energy during off-peak hours. This can reduce the peak electricity demand and also store renewable energy, accounting for the changing energy demand for each day.

CONCLUSION

In conclusion, reducing the environmental footprint presented by the growing data center industry requires several strategies that relate to the sustainable construction, design, and maintenance of data centers. In terms of construction, adopting eco-friendly materials like green concrete and steel slag can significantly reduce reliance on traditional resource-intensive materials. Moreover, design choices such as underfloor air distribution systems, energy recovery systems, and economizers can all optimize energy efficiency. Maintenance suggestions such as liquid cooling systems and thermal energy storage can help integrate more renewable energy sources, lowering net greenhouse gas emissions. Overall, these strategies focus on balancing technological advancement and environmental stewardship by making data center construction, design, and maintenance more sustainable.

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