

IMPACT OF ENERGY EFFICIENT GREEN DATA CENTERS: STRUCTURES AND METHODOLOGIES SYSTEMATIC REVIEW

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ABSTRACT

The increasing demand for digital services has led to a significant rise in energy consumption and carbon emissions from data centers. This systematic review explores the multifaceted impacts of energy-efficient green data centers, focusing on energy use, lifecycle impacts, sustainable information and communication technology (ICT), sustainable energy, and sustainable cooling solutions. By synthesizing current literature, the paper identifies key strategies and methodologies that can reduce the environmental footprint of data centers while maintaining operational efficiency. The review highlights the importance of integrating renewable energy sources, optimizing cooling technologies, and implementing robust energy management practices to achieve sustainability goals. Additionally, it emphasizes the necessity of collaborative efforts among stakeholders to develop innovative solutions that will facilitate the transition toward greener data center operations.



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1. INTRODUCTION

Organizations have seen a worldwide effort in recent years to combat global warming by using ecologically conscious products and technologies. Data centers were still called the backbone of the internet - these are large places, where they not only handle, but also keep and distribute the enormous quantities of data that constitute this digital realm (Belkhir & Elmeligi, 2018; Orumwense & Abo-Al-Ez, 2020). However, their very existence can be interpreted as the growing demand for computing power, i.e., more electricity consumption. This surge of

energy consumption is not only one of the major threats to our global energy resources, but it also causes environmental destruction, which is one of the biggest factors of quick global warming (Huang et al., 2020; Lokmic-Tomkins et al., 2022). The escalating dependence on data centers for digitization usually begs the question of how to make them energy efficient. It is not hard to see the fact that old-fashioned data centers use much energy, from the necessity of the operation of servers, the establishment of connectivity around the world to the cooling systems that keep temperatures within a set range. The high energy consumption of the

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equipment is not only a driver of the costs of business operations but also the cause of the environmental issues through the increase in greenhouse gases (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2019; 2021). Data centers that are power-efficient are the ones that are capable of dealing with these challenges in a technological way: virtualization, the use of renewable energy, efficient cooling, and intelligent energy management are among a complicated array of tools they may use (Lokmic-Tomkins et al., 2022). The prosperous path to that is depicted by the organization actions and their efforts reduce their carbon footprint, slash their operational expenses, and com-externally grow with the renewable destroying of the old growth while, at the same time, the demand for data processing and storage is always ever-increasing. A significant number of firms and organizations adopt green IT strategies through the use of sustainable technologies in their processes aiming for making them environmentally friendly, cheaper and self-sustaining (Green IT Initiative, 2022; Gupta et al., 2024). The demand for data centers is at an all-time high, driven by an ever-increasing reliance on digital technologies. However, this surge in demand poses significant environmental challenges. Data centers are major consumers of energy and significant contributors to greenhouse gas emissions. According to the International Energy Agency (IEA), data centers accounted for about 1% of global electricity demand in 2020, a figure projected to increase significantly as digital services expand (International Energy Agency, 2021). Data centers are essential components of modern digital infrastructure, yet they pose significant challenges regarding energy consumption and environmental sustainability. This review aims to systematically analyze the structures and methodologies employed in energy-efficient green data centers, emphasizing their impact on energy usage and ecological footprints.

2. DATA CENTERS AND ENERGY USE

Data centers play a crucial role in the digital economy. They power cloud computing, as well as streaming services. Yet, the central part of their operation is a massive energy consumption process to sustain the servers, storage devices, and cooling systems. The data we get from the sources we trust indicates that data centers consume a large portion of the global energy, which keeps growing as digital service demand rises. That energy use, however, does not just drive the operational expenses, but it also is behind numerous environmental problems because many data centers continue to use non-renewable energy sources. The data center energy usage can be divided into two categories as in (Kant, 2009; Parvez, Ponnusamy, Santhosh, & Kamra, 2023). for example: energy used by the IT equipment (e.g., servers, networks, storage, etc.), and the usage of the infrastructure facilities (e.g., cooling and power conditioning systems). The energy consumption of these two subcomponents relies on the configuration of the

data center and the power quality of devices. based on the data release by the Infotech group the cooling infrastructure accounts for the vast majority of energy consumption (50%) in a typical data center (Aebischer & Hilty, 2015; Andrae & Edler, 2015), while servers and storage devices (26%) is being the second most energy consumer in the energy hierarchy.

The environmental impact of data centers encompasses their lifecycle from construction to startup and to termination and dismantling. During construction, material resources such as steel, concrete, and appliances are extensively used. But the main sources of production and transportation of material considerable amounts of carbon. Data centers become energy-sucking patches. (International Telecommunication Union, 2020; 2023). Firstly, they grab hold of the massive amount of energy needed to power servers, connecting devices, and cooling systems. Such reliance of energy, which is generally extracted from fossil fuels, is the foremost reason for greenhouse gas emissions and also the trigger factor causing energy deficiency globally. Additionally, consistent hardware replacement, as such, becomes a matter of the e-waste problem. Those components such as servers, storage devices, and batteries are replaced more often than not due to a demand for performance or a mark of technological progress. The disposition of these components can lead to the danger of leakage of toxic materials and this, in its turn, constitutes a threat to both ecosystems and human beings. When a data center is decommissioned, infrastructure and materials are dismantled, and reusable or recyclable materials are disposed of or recycled, a situation that, if not appropriately mitigated, may pose further environmental harm.

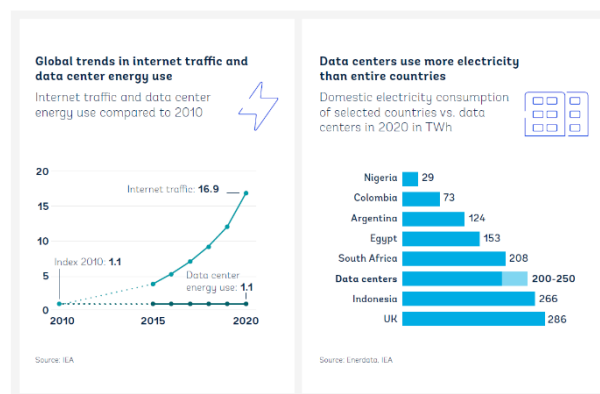


Figure 1. Data Centers' Energy Use Magnitude and Trends Data Centers

However, steps like shifting to energy-efficient development, utilizing renewable energy methods, the extension of hardware life cycles through re-use so as to avoid recycling, and conforming to the essential various aspects of the circular economy have to be taken to turn around the data center's profound life-cycle impact to sustainability. Between 2015 and 2021, the International Energy Agency reported a 260% rise in data center workloads, underscoring the growing reliance on digital technologies. This increase is driven by the global rise in

data generation and the demand for cloud computing services. Technological advancements have improved data processing efficiency, thereby increasing overall demand for data center capacity.

2.1 Global Trends in Internet Traffic and Data Center Energy Use

From 2010 to 2020, internet traffic grew substantially, paralleling the trends in data center energy use. As illustrated in Figure 2, this dynamic reflects the balance between increased digital activity and enhanced energy efficiency measures implemented within data centers.

Power use effectiveness (PUE) is often cited when discussing green data centers. It is a measure of a data center's energy allocation and is calculated by dividing total energy that a center consumes by the energy that the IT equipment consumes. The closer PUE is to 1.0, the more efficient it is.

For instance, a PUE of 3.0 means that the total energy that a data center consumes is three times the energy required solely for powering the IT equipment. PUE serves as a multiplier for determining the actual effect of a system's power requirements. To illustrate, if a server uses 900 kWh of electricity, and the data center has a PUE of 3.0, the utility grid would need to supply 2,700 kWh of energy to deliver the required 900 kWh to the server. Influences on PUE include cooling systems, temperature, humidity, and data center design. Warmer climates require more cooling. Energy needs and hence PUE vary geographically. Although PUE is a useful metric, it should be assessed in combination with other metrics.

3. LIFECYCLE IMPACT OF DATA CENTERS

Data centers have an environmental effect throughout their lifecycle, including materials for the building, raw materials and energy to manufacture ICT equipment, energy, refrigerants and water for operations, and energy and pollutants during decommissioning. Figure 2. demonstrates a simplified data center lifecycle, including material and energy use in each phase and opportunities for material and energy reuse.

Data centers exert an environmental impact throughout their entire lifecycle, from construction to decommissioning. Key phases include:

- **Design and Manufacturing.** Incorporating sustainable design practices minimizes resource consumption and waste.
- **Operation and Maintenance.** Employing energy-efficient cooling and power distribution systems can significantly reduce operational waste.
- **End-of-Life Management.** Adopting circular economy principles facilitates recycling and refurbishing, mitigating environmental impact.

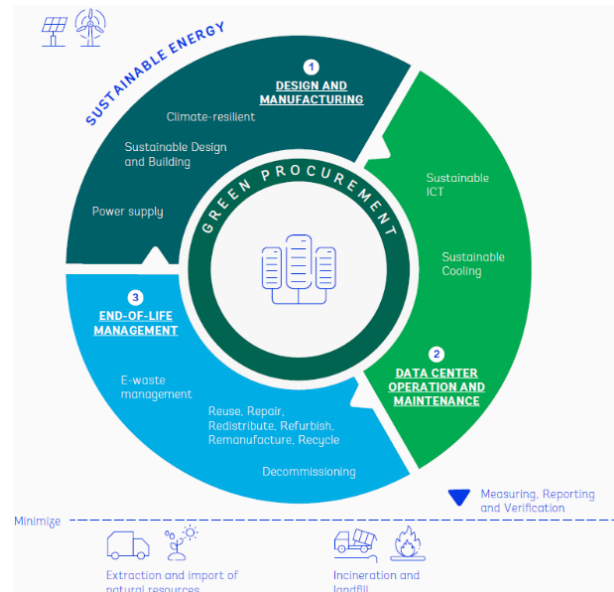


Figure 2. Data Center Lifecycle

3.1 Circular Economy Principles

Reuse, recycling, and refurbishment comprise a few of the strategies employed within the circular economy model to keep materials and goods flowing. Its main goal is to reduce waste generation while improving natural processes in a sustainable manner. Three fundamental ideas are essential to a circular economy's operation: reducing waste and pollution, reusing materials and products, and restoring the environment. By embracing circular economy principles—designing for durability and reparability, reusing equipment, and employing renewable materials—data centers can significantly lower their ecological footprints. Transitioning to renewable energy sources is essential, yet the continuous power demand of data centers poses challenges, particularly in low- and middle-income countries (LMICs). Integrating data centers into the broader energy system can enhance sustainability, address grid congestion, and optimize the utilization of residual heat.

4. SUSTAINABLE DESIGN AND BUILDINGS

Data centers exert an environmental impact throughout their entire lifecycle, from construction to decommissioning. Key phases include:

- **Building Envelope and Location.** Data center design begins with the building envelope, with location and structure affecting operational reliability, resource use, and energy efficiency. Environmental risks such as proximity to natural hazards are essential considerations in site selection. A common challenge is the focus on the operational phase, often neglecting sustainable design and construction. Addressing emissions during design and construction establishes a foundation for long-term efficiency and sustainability.

- **Sustainability and Cost Considerations**, Planning new data infrastructure requires a holistic view of total cost of ownership, including initial capital, operational expenses, and end-of-life facility disposal. Although sustainable options might entail higher initial costs, they yield long-term financial and environmental benefits. Proper dimensioning, or right-sizing, is critical; an underutilized data center can negate potential sustainability gains.
- **Underutilization Challenges in LMICs**, Many lower- and middle-income countries (LMICs) experience underutilization of data centers due to factors such as limited awareness of efficient practices and insufficient public sector capacity. Addressing this requires investment not only in infrastructure but also in demand-side initiatives, like capacity building and training, to maximize the value and efficiency of data centers.

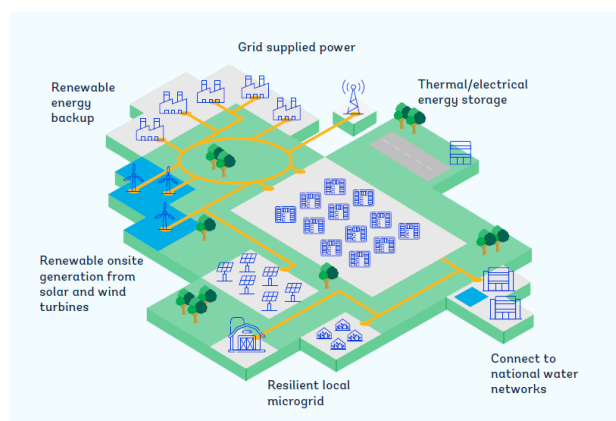


Figure 3. Data Center Site Selection

4.1 Key Steps to Enhance Sustainability

- **Refurbishment of Existing Facilities**, before constructing new facilities, consider upgrading existing ones. Modernizing a data center can enhance efficiency and sustainability while reducing costs and embodied carbon emissions. Refurbishment must account for space limitations and site-specific constraints, yet offers opportunities for integrating energy.
- **Site Selection**: Consider environmental assessments, risk profiles, climate suitability for cooling, and opportunities for renewable energy integration. Collaboration with auxiliary industries to reuse energy or heat can further reduce the environmental footprint.
- **Dimensioning and Future-Proofing**: Right-sizing prevents inefficiencies. Overprotection often leads to underutilized servers consuming disproportionate energy. Virtualization can optimize capacity, and modular designs allow for scalable expansion.
- **Eco-Friendly Materials and Design**: Use sustainable materials like cross-laminated timber instead of concrete or steel. Modular, containerized

designs reduce waste and energy demand (Lee & Kim, 2022). Renewable materials and recycling efforts minimize the carbon footprint during construction.

- **Standards and Certifications**, Adopting standards such as EN50600 and ISO/IEC 22237 ensures that data centers meet sustainability benchmarks. EDGE certification can further guide the development of cost-effective and marketable projects tailored for emerging markets.

5. SUSTAINABLE ICT

The ICT market is uncertain, scale-dependent, interrelated, and intricate. It is a dynamic industry that brings challenges to countless other industries. Furthermore, there may be a rebound effect; despite improvements in device energy intensity, the scale of use has grown at a rate that has raised overall energy consumption. The ICT industry is accountable for roughly 2% and 2.5% of greenhouse gas emissions worldwide. ICT consumption is increasing at a pace of 20% annually, which can be worrying even if this may seem like a little percentage. Therefore, in order to lessen environmental effects while simultaneously driving overall growth, it is critical to balance the swift increase of computer resources with green technology. It is essential to take consideration of the whole ICT infrastructure creation process in order to reach the goals of ICT sustainability. For IT producers, minimizing environmental effect should be a basic tenet of all ICT component design and production.

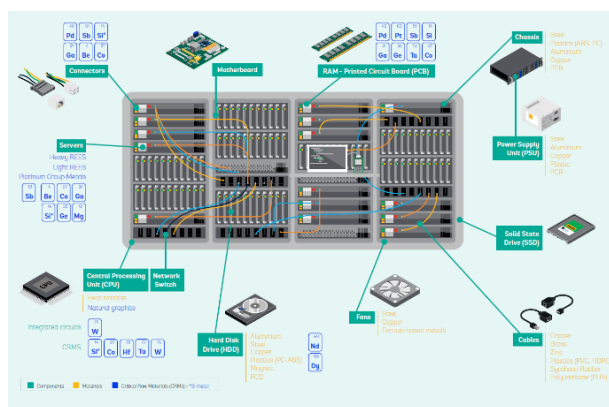


Figure 4. Typical Information and Communications Technology Equipment in a Data Center

Sustainable ICT (Information and Communication Technology) in green data centers involves a holistic approach that integrates energy-efficient technologies, renewable energy sources, advanced cooling solutions, and responsible resource management. By prioritizing sustainability, data centers can reduce their environmental impact while maintaining high levels of performance and reliability. This aligns with the growing demand for environmentally responsible practices in the tech industry, contributing to the overall goal of reducing

carbon footprints and promoting sustainable development. ICT equipment in data centers is resource and energy intensive to manufacture and requires power and cooling to operate. Figure 4 shows typical data center equipment and the materials used to manufacture it.

5.1 Choosing Energy-Efficient Equipment

In order to accomplish energy efficiency, the continuing buildup of computer equipment in data center design has forced surveillance, estimation, and supervision of these installed components' performance. Network equipment accounts for 2 percent to 5 percent of energy use in a typical data center, storage equipment uses 20 percent to 30 percent, and servers consume the rest (Deutsche Welle, 2020; European Telecommunications Standards Institute, 2020; Lamendour, 2022; Masanet, Shehabi, Lei, Smith, & Koomey, 2020). Although the initial cost of procuring energy-efficient hardware is likely to be higher, it can result in lower lifecycle costs, making it a more-cost-effective choice in the long run. A wide range of ICT equipment might not be available in some LMICs. Although ICT equipment historically has become exponentially faster, this trend has slowed, so investing in refurbished equipment can be a good option. Refurbishing equipment leads to longer intervals between maintenance shutdowns, increasing operational efficiency and reducing disruption of regular operations.

6. SUSTAINABLE ENERGY

6.1 Sustainable Energy Practices for Data Centers

Data centers are highly energy-intensive, consuming between 10 to 100 times the electricity per floor area compared to typical commercial buildings. Effective energy management is crucial to minimize both energy consumption and costs. Strategies for sustainable energy use in data centers include using renewable energy, reusing residual heat, and implementing onsite energy generation, though these may require backup generators for baseline power needs. The capital investment and operational costs for renewable systems can pose barriers, necessitating an assessment of long-term benefits, cost savings, and return on investment.

6.2 Renewable Energy Integration

There are three categories of renewable energy sources that we can utilize to power a data center. Certain green energy sources, like solar panels and wind turbines, depend on the availability of natural resources in the environment, such as sunlight and wind speed (Data Center Dynamics, 2022; Yadav, Azad, & Vaish, 2020). These sources are classified as intermittent power supplies due to their variable output over time. Additionally, several new green energy technologies—including fuel cells, bio-fuel gas turbines, and biomass

generators—can provide consistent green energy through the combustion of different sustainable fuels. Renewable energy availability and infrastructure are key in determining the viability of renewable-powered data centers, particularly in regions with abundant resources like solar, wind, and geothermal energy. Global cloud providers often prioritize renewable energy access in their investment strategies, as renewable projects hold potential for both environmental and operational benefits. To ensure a steady supply, data centers can establish power purchase agreements with renewable providers or install onsite generation systems like solar panels or wind turbines (Schulze, 2022). These renewable sources, coupled with energy storage solutions, reduce emissions and provide energy stability.

6.3 Energy Management Approaches

Data centers must carefully balance performance and sustainability in order to enhance energy and operational efficiency. Data center administrators might boost their ability to compete and reduce operating costs by coping with energy use. Additionally, by lessening carbon emissions and dependence on non-renewable energy sources, energy-efficient data centers are crucial in reducing the environmental effect of the IT industry. The application of advanced asset performance and maintenance strategies is a possible method for tackling these issues. This calls for a major shift in maintenance procedures from reactive to proactive. Data center operators may get important insights into equipment performance, foresee possible issues, and carry out preventive measures by leveraging cutting-edge technology like machine learning and predictive analytics.

Implementing an energy management plan is foundational for sustainable operation. This includes monitoring, regulating, and conserving energy based on specific performance metrics, often guided by standards such as ISO 50001 (International Finance Corporation, 2017). Sub metering can provide granular insights into energy usage, while advanced digital tools like IoT and AI systems enable precise monitoring, predictive maintenance, and optimization at the unit level. Adjusting energy use according to renewable availability can further lower costs and environmental impact.

6.4 Energy Storage and Backup Solutions

Diesel is dominating the prevailing backup power market, which leads to climate change and presents health hazards owing to greenhouse gas emissions and air pollution. Diesel generators additionally waste an abundance of energy given that they are demanding to maintain, require regular testing, and usually run below their maximum capacity. On the flip hand, data centers can store clean energy adopting battery energy storage systems in conjunction with renewable energy sources like solar or wind, which will mitigate the negative

emissions linked to diesel and promote a more sustainable future. Battery energy storage systems provide a useful way for organizations to accomplish their social, governance, and environmental goals and strengthen their environmental responsibility.

Presently, due to the intermittent nature of renewable sources, energy storage solutions, such as batteries, are essential for maintaining continuous power. These systems can store excess energy during peak production times and supply it when demand is high. Modular and scalable renewable setups allow data centers to adjust energy capacity as needed, stabilizing the grid network and reducing peak loads. Additionally, energy-efficient uninterruptible power supplies (UPS) can ensure operational reliability during unexpected outages.

6.5 Case Studies in Sustainable Data Centers

- **Scala Data Centers, Latin America** (Scala Data Centers, 2023): Scala Data Centers exemplifies sustainability in action, being the first in Latin America to operate on 100% certified renewable energy. It achieved a power usage effectiveness (PUE) of 1.5, significantly better than the regional average. Scala's initiatives, recognized by the iMasons Climate Accord, underscore the environmental and operational benefits of renewable-focused strategies.
- **Odense Data Center, Denmark** (Facebook, 2021): The Facebook data center in Odense, Denmark, showcases an exemplary approach to energy efficiency. The facility employs highly efficient hardware, indirect evaporative cooling, and wind energy. Notably, it repurposes waste heat, providing enough recovered energy annually to heat 6,900 homes via a district heating system supported by a heat pump facility. This project underscores the potential of waste heat recycling to benefit local communities while enhancing the energy efficiency of data centers.

7. SUSTAINABLE COOLING SOLUTIONS IN DATA CENTERS

Efficient cooling is essential for data centers, where high-performance computing and server technologies generate substantial heat that must be managed to prevent equipment damage and downtime. Cooling systems often consume over 40% of a data center's total energy use, with this percentage rising in regions with high temperatures and humidity. According to ASHRAE (ASHRAE, 2019; 2021), the recommended temperature range for A1 to A4 class hardware is 18°C to 27°C, which is higher than many data centers are configured. To meet the unique cooling needs across different climates, data center operators are innovating with both air and liquid cooling solutions. However, smaller data centers may struggle to balance reliability

with energy efficiency, often leading to overcooling and uneven air distribution. Additionally, traditional cooling methods place significant strain on local water resources, intensifying the need for sustainable water management alongside efficient cooling strategies.

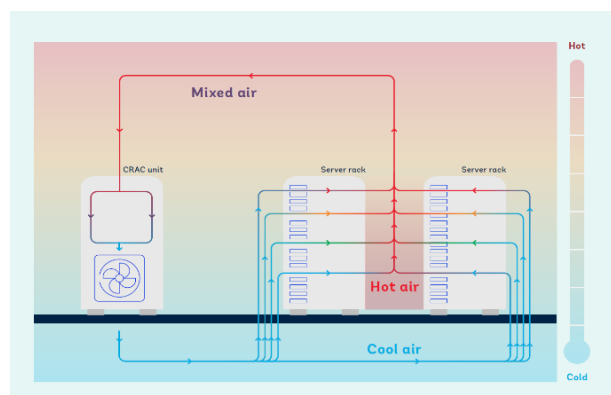


Figure 5. Raised Floor and Overhead Air Supply System

7.1 Key cooling solutions include:

- **Natural or Ambient Air Cooling**, Utilizing external air when conditions allow reduces reliance on energy-intensive mechanical cooling. For example, Equinix's SP3 data center in São Paulo uses indirect free cooling methods that harness cooler external air, reducing energy costs and emissions.
- **Advanced Airflow Management**, Proper airflow techniques, such as hot and cold aisle containment, prevent mixing of cool and hot air, improving efficiency and reducing hotspots. Raised-floor setups and optimized server rack layouts can further enhance heat dissipation.
- **Liquid Cooling Technologies**, Liquid cooling consumes less energy than traditional air-based methods and can be used in closed-loop systems that minimize water use. This technology is highly suitable for facilities with water scarcity concerns, as it supports water-saving objectives while maintaining effective cooling.
- **Alternative Refrigerants**, Traditional refrigerants like hydrofluorocarbons contribute significantly to global warming. Switching to low-global warming potential refrigerants, such as hydrofluoroolefins or natural options like ammonia, could reduce emissions by up to 50 gigatons of CO₂ equivalent between 2020 and 2050. Data centers should also implement monitoring systems to detect leaks and ensure proper refrigerant management.
- **Waste Heat Utilization**, Capturing and repurposing waste heat can provide energy for external applications, such as district heating. For instance, the Facebook Odense data center in Denmark uses waste heat to power nearby residential heating systems, enhancing local energy efficiency and sustainability (Facebook, 2021).

7.2 Case Studies in Sustainable Cooling for Data Centers

The Cooling infrastructure refers to the hardware that generally consists of computer room air conditioning (CRAC) units, chillers and cooling towers (Smith & Brown, 2023). The cooling infrastructure represents around 15–20% of the total energy consumption of the data center. The Power infrastructure ensures that reliable conditioned power at the appropriate nominal voltage and frequency is delivered to both the IT equipment in the racks and the cooling infrastructure.

- **Free Cooling model analysis of Iran data center** (Deymi-Dashtebayaz & Valipour Namanlo, 2019):

The study studied techno-economic potentially in ten cities of Iran with different weather conditions via using Air-Side Economizer (ASE), Water-Side Economizer (WSE) and Combined Air or Water Economizer (CAWE) operation mode to cool a data center. The potentials were examined in a case study of Mashhad municipality's data center and the result was generalized for all cities during a year. As for all cities except coastal ones, CAWE operation mode could save both energy and cost. In most of the cities, it is found that CAWE cooling mode increases Power Usage Effectiveness (PUE) somewhere between 10% to 12% over the data centers. The cooling approach adapted in Brazil proves that these free cooling systems provides the main advantages for the data centers. This is not due to the power of data center environmental infrastructure but also because of the natural resources of nature, such as outside air and water, are used to the temperature of the servers and equipment. This strategy involves minimizing the use of energy-intensive mechanical cooling systems, which have then resulted in the saving of energy and as a result, the operations cost has been reduced.

- **Waste Heat Recovery in Denmark** (Huang et al., 2020):

In the Nordic countries, such as Finland and Denmark, there are several green data centers. This is because these regions present a number of benefits such as a climate free from violence, affordable electricity, stable political conditions, a green electrical grid, and—above all—a large share of renewable energy sources in the power mix. In Denmark, a number of information centers have recycled their waste heat for the benefit of the community. Many of these data centers in Denmark have repurposed their waste heat to advantage the area people, which includes:

Microsoft records center in Høje-Taastrup. (Microsoft, 2023; Roach, 2018). This records middle will produce sufficient warmth to warm around 6,000 neighborhood houses. The project is a collaboration with VEKS, a district heating agency that harnesses surplus warmth from nearby commercial groups and buildings.

Odense statistics center (Facebook, 2021)

These statistics middle captures and recycles extra heat generated by way of the servers to offer warmth to the local people. The heated air from cooling the servers is used to raise the temperature of water, that's then furnished to a warmth pump installation.

The Facebook data center in Odense, Denmark, (Facebook, 2021) highlights an innovative waste heat recovery system. This facility captures waste heat from its servers and channels it to a district heating system, providing warmth for up to 6,900 homes annually. Powered entirely by renewable wind energy, this system recycles approximately 100,000 MWh of energy each year. It illustrates the potential for data centers to contribute to community energy needs while reducing their environmental footprint.

- **Chimney-Style Airflow in South Korea** (World Bank, 2022):

Energy performance is seen as essential to cost control by LG CNS, its operational personnel, and capacity clients. Fast trends, however, have significantly improved IT performance in recent years. Data centers must provide more space for power and cooling infrastructure since modern processors generate more heat. LG CNS came to the conclusion that it needed to upgrade a cooling device designed for extremely dense data centers. The redesigned cooling device would also be more power-efficient, they projected.

The LG CNS data center in Busan, South Korea, utilizes a unique “chimney-style” airflow design that efficiently exhausts hot air from server rooms (figure 6).

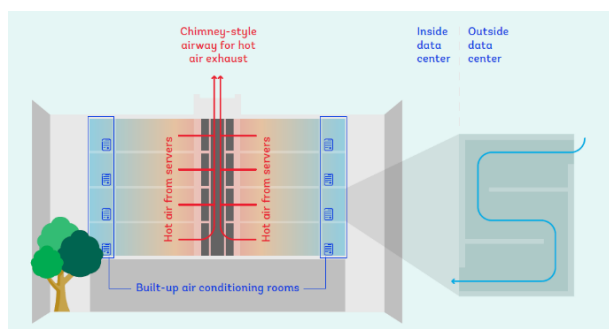


Figure 6. Chimney-Style Airway

With an impressive Power Usage Effectiveness (PUE) of 1.39 on average, and as low as 1.15 in winter, the center operates efficiently by limiting cooling needs. This facility's use of a hybrid cooling system, called the Built-Up Outside Air-Cooling System, is tailored to seasonal variations, optimizing energy use and further improving cooling efficiency.

- **Bahnhof data center in Stockholm Sweden** (Wahlroos et al., 2018):

Bahnhof is a Swedish internet service provider that supplies excess heat and cooling from its two data centers, Bahnhof Thule and Bahnhof Pione, to Stockholm Exergi, an energy company based in Stockholm. Stockholm Exergi states that this arrangement offers several benefits for both the district heating company and the businesses supplying and selling surplus energy. One key advantage for Stockholm Exergi is reduced production costs, as the incoming heat substitutes for more expensive production methods. For the data centers, advantages include revenue from energy sales that would otherwise be lost, enhanced utilization of the cooling systems, and the potential for improved overall system reliability. Stockholm Exergi utilizes a pricing model that fluctuates according to the energy demand within the network. Consequently, prices decrease when demand is low and increase when demand is high. On particularly cold winter days, the value of the heat supplied can reach up to ten times its value on a typical summer day. Therefore, the surplus heat generated by the heat pumps is primarily utilized in the district heating network when the outside temperature is below 7 °C, which occurs for about half of the year. Although there is consistently a demand for heat within the district heating network, Bahnhof retains the right to supply heat to Stockholm Exergi at any point in time.

- **Yandex data center in Finland** (Forero & Rahman, 2021):

The Finnish energy company Nivos Oy has partnered with Yandex, the Russian search engine, to harness waste heat from a data center in Mäntsälä, Finland. The excess heat is captured by Yandex then sold to Nivos Oy, which then disintegrates it across the neighborhood. This cooperative endeavor has produced financial benefits for Yandex, Nivos Oy, and the local population. At present, nearly half of the town's heating supply comes from the extra heat generated by the data center, which results in a 12% decrease in energy costs for Mäntsälä residents. Additionally, by using the data center's recovered heat rather than energy produced by fossil fuels, Nivos has reduced its carbon emissions by 40%.

Yandex has been providing excess heat to Nivos since 2015. In November 2018, the company erected a new system in a section of the plant, unveiling its second generation of heat recovery technology. This development made it possible to recover 60–80% of the extra heat, making it roughly than twice as much energy as was recovered in the original iteration. After the new technology is completely integrated across the data center, Yandex expects to reuse 90% of the facility's energy. According to the Finnish innovation fund "Sitra," more than half of Mäntsälä's heating needs are satisfied by waste heat from the data center. recuperation, 500,000 cars would be taken off the road, which would result in a reduction in emissions.

8. CONCLUSION AND FUTURE SCOPE

In conclusion, the transition to energy-efficient green data centers is not only essential for mitigating climate change but also for enhancing operational efficiency and sustainability in the digital sector. By adopting sustainable energy practices, implementing advanced cooling solutions, and considering the lifecycle impacts of data center operations, stakeholders can significantly reduce energy consumption and carbon emissions. This survey underscores the need for a holistic approach that integrates technological innovations with effective management strategies. As the demand for data processing continues to grow, embracing sustainability will be crucial for ensuring that data centers can meet the needs of the future while minimizing their environmental impact. Ongoing research and collaboration among industry leaders, policymakers, and researchers will be vital to advancing green data center initiatives and fostering a sustainable digital economy.

- **Artificial Intelligence for Autonomous Energy Management**, AI-powered energy management systems will play a critical role in future data centers. Using machine learning algorithms, these systems can autonomously adjust energy use, predict peak loads, and optimize cooling dynamically. By continuously learning from real-time data, AI can reduce unnecessary power consumption and lower operational costs, making data centers more efficient and resilient to changing demands without human intervention.
- **Development of Ultra-Low-Power Processors**, Leading tech companies are developing processors specifically designed for energy efficiency, focusing on ultra-low-power architectures. These processors consume significantly less energy, generating less heat while maintaining high performance, which is especially valuable for data centers handling AI or machine learning tasks. This trend promises to minimize cooling needs and further reduce data center energy costs, aligning with green energy goals.
- **AI-Driven Predictive Maintenance**, Predictive maintenance powered by AI will enhance data center efficiency by identifying potential equipment issues before they lead to failures or energy inefficiencies. AI algorithms analyze data from sensors monitoring servers, cooling systems, and other infrastructure to predict when maintenance is needed. By addressing issues proactively, data centers can prevent downtime, reduce repair costs, and optimize energy use, as equipment operates within peak efficiency. This approach minimizes waste, lowers operational costs, and prolongs the lifespan of data center hardware

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