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Energy Consumption of Data Centers and Taxing CO_2: Understanding the Carbon Footprint

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ABSTRACT

Data centers are critical in today's digital business complex and underpin a vast range of applications; these include cloud computing, social networking, and artificial intelligence. However, the increased volume of data and processing requirements, along with the increasing scope of digital services, has raised concerns about energy consumption and the environment. Electrical consumption by data centers was estimated in 2018 to be at 200 TWh globally, which accounts for about 1% of total power usage; however, about 26% of this electricity comes from coal and natural gas. This energy consumption accounts for approximately 0.3% of the global CO_2 emissions, initiating the debate on the sustainability of data centers, given the current trends of increasing digitization. In this paper, the author is concerned with aspects related to data centers' environmental footprint, specifically consumption, CO_2 emissions, and the possible impact of carbon taxation systems. Scholars also mention others, such as the energy grid and efficiency and utility measures like PUE- Power Usage Effectiveness. It also outlines the current process of lowering carbon emissions, such as shifting to renewables, enhancing cooling techniques, and applying modular design in data centers. Leading CSPs like Google, AWS, and Microsoft are key examples of the opportunities to lower emissions by procuring renewables and utilizing AI cooling. The paper is, therefore, intended to help policymakers, technology firms, and society at large employ sustainable remedies in data center operations. However, it highlights the need for adopting new regulations, technology, and international cooperation in the promotion of the expansion of digital innovations together with a sustainable environment. As the data centers advance through the margin, incorporating green measures will be essential for efforts to contain the environmental impact.

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Introduction

Modern business has become almost unthinkable without data centers, the primary engines of many services now familiar to millions of users – cloud storage, social networks, online stores, and artificial intelligence. As central computing facilities that facilitate data storage, computing, and network command, data centers allow for the functioning of many Web-based applications that provide life's functionality. Due to a rising need for Internet services and the expansion of digital services, the facilities required to support data processing and storage have grown and extended their facilities worldwide. While this has dramatically expanded the Internet provision, it has also done this at a significant cost of energy consumption and environmental degradation. The primary concern for data center energy consumption is that it operates on full-utility power to support IT equipment, cooling systems, and network facilities. Global data centers consumed around 200 TWh of electricity in 2018, equivalent to 1% of the world's electricity. This energy demand has raised alarms since the energy used by data centers is often sourced from carbon sources such as coal and natural gas. Such sources are carbon dioxide (CO2) and other greenhouse gases exacerbating global climate change.

Reducing the environmental footprint of data centers is a critical issue to address as the use of digital services expands. The advancement towards sustainability across the world has made the carbon emissions connected to data centers come into focus for governments, organizations, and tech giants seeking to address their negative impacts. Proposals for reducing CO2 emissions are not solely concerned with environmental conscience but also compliance with legislation and satisfying the customer demand for environmentally friendly companies. The increasing number of companies adopting policies to maintain sustainable operations also puts pressure on data center carbon emissions. Many organizations, including Google, AWS, and Microsoft, are moving towards optimizing their carbon footprint through procuring renewable energy and creating efficient energy-based technologies. Still, the smaller data centers and colocation facilities can barely meet the sustainability goals because of financial and operating limitations. This difference underlines the importance of arriving at solutions, besides regulations and benchmarks, which would affect all data center industry players and encourage them to reduce energy consumption sustainably.
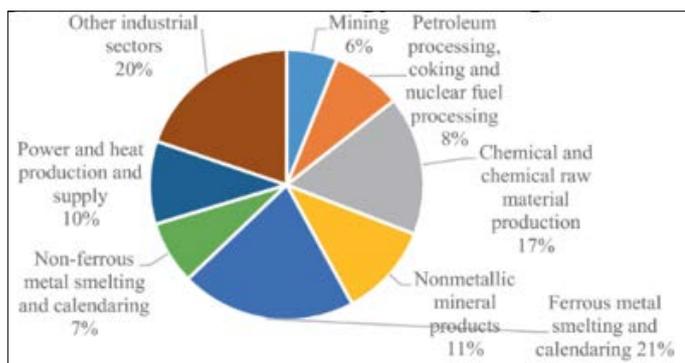
Figure 1: End-Use Energy Consumption & CO2 Emissions

The objective of this article is to outline the current use of data centers as information storage centers, the current levels of energy usage and the effect it has on the environment, an analysis of the possibility of taxing CO2 as well as exploring other measures that may be implemented to reduce the amount of CO2 emission. The article will also review technology and strategy development aimed at increasing efficiency and the use of renewable energy in the industry by industry players. Discussing these topics, the article will reveal the prospects and difficulties that the process of data center greening faces. This article intends to disseminate information to the various stakeholders, policymakers, technology firms, and the general public that data centers matter in the digital economy and the urgent need to address the issues of green solutions. It reinforces the idea of an ongoing process to seek and advance new and efficient solutions and apply regulatory measures that would help strike a balance between digital development and environmental responsibility in the field of the data center market.

Energy Consumption of Data Centers
Data centers have become critical to the functioning of a contemporary ecosystem, offering services ranging from cloud, A.I., and streaming services, among others. Since more people use digital service providers, there is an increase in energy demand, which contributes to environmental challenges. These challenges entail information on the primary energy consumers, trends, and particular area uses, which is critical in nurturing better solutions.

Overview of Data Center Energy Use
The energy consumption of data centers is primarily driven by three components: Computer gear and networking, as well as electrical and cooling systems. About 46% of energy is consumed by I.T. loads, which include servers, storage, and network devices for data management and distribution. Servers are known to utilize considerable energy because they are expected to constantly run to handle large amounts of data [1]. For a cooling system to work efficiently in protecting devices from overheating, it is another factor that consumes a large amount of energy. In the past, air cooling methods have been predominant despite their common characteristic of high energy consumption. This has

engendered the application of better technologies like liquid cooling and free-air cooling, which use less energy but have improved efficiency. Finally, the equipment used for data transfer via optimizing a network, an essential component in mass cloud-based operations, comprises a significant share of total data center energy consumption.

Global Energy Consumption Statistics
Data centers estimated that electricity consumption as a percentage of electricity in 2018 was approximately 2% – around 200TWh. This enormous amount of energy needed can be attributed to the growth of the digital industry, such as cloud and big data artificial intelligence. With the increase in data processing requirements, there was expected to be an increase in energy demand, but the latest trends depict stabilization of energy usage due to efficiency [2]. Advanced developments in server, cooling structure, and virtualization techniques have allowed decentralized workloads to be centralized, thus having less demand for new equipment.
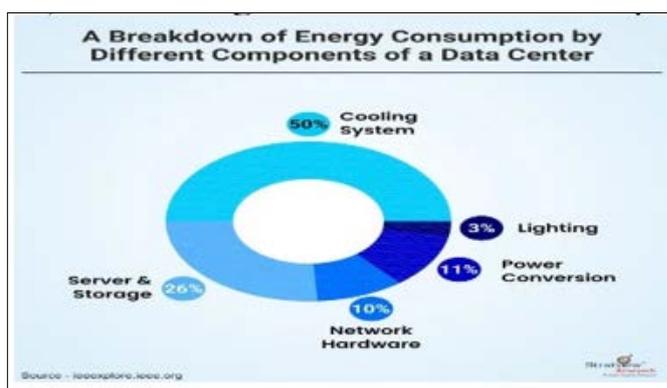

Figure 2: Energy Consumption of Data Centers

Cost savings have been noted by purchasing energy-efficient servers and storage, which offer better processing services at minimal power consumption levels. Furthermore, virtualization has enabled several virtual servers to be hosted on a single physical server, thus reducing the overall number of servers needed. This means energy is saved when computing and cooling the devices [1]. However, some companies have adopted AI-driven cooling technologies that regulate the cooling system's power depending on the real-time temperature and workload. For instance, Google developed an artificial intelligence-powered cooling system that helped it cut down on the energy consumed by data centers for cooling by up to 30%, which is the significance of new and innovative energy conservation practices [3]. This stabilization comfortably sits with data center energy use plans, which otherwise would have been foreseen to grow exponentially. However, the latest stats reveal that network energy consumption is rising slower than data traffic, thanks to these innovations. Nevertheless, further digital infrastructure development will remain an energy efficiency issue.

Table 1: Summary of Energy Consumption and Efficiency Measures in Data Centers

Category	Details
Primary Sources of Energy Consumption	- IT Equipment: Servers, storage devices, and networking equipment.
	- Cooling Systems: Traditional air-based methods, liquid cooling, and free-air cooling.
	- Network Infrastructure: Facilitates data transfer and consumes significant energy, especially in cloud environments.
Global Energy Consumption (2018)	- Approximately 200 TWh, or 1% of global energy consumption.
	- Energy usage remained stable despite growing demand due to efficiency improvements.
	- Efficiency measures include energy-efficient servers, virtualization, and AI-driven cooling.
Efficiency Improvements	- Energy-efficient servers and storage systems: Greater processing power with less energy use.
	- Virtualization: Allows multiple virtual servers on one physical machine, reducing hardware needs.
	- AI-driven cooling: Adjusts cooling output based on real-time data; e.g., Google reduced cooling energy by 30%.
U.S. Energy Consumption	- Data centers accounted for about 3% of national electricity use, equating to 70-80 TWh per year.
	- Major players include AWS, Google Cloud, and Microsoft Azure.
	- High energy consumption due to AI, big data, and streaming services.
Cooling Energy Use in U.S. Data Centers	- Cooling systems contribute 30-40% of total energy consumption in some facilities.
	- Adoption of liquid cooling and modular data center designs to optimize energy use.
Energy Reduction Strategies	- Modular Data Centers: Scalable, standardized units that optimize cooling efficiency.
	- Renewable Energy: Use of wind, solar, and other renewable sources to reduce carbon footprint.

Data Center Energy Use in the U.S

The USA data center consumes about 3% of the electricity, about 70-80 TWh annually. This significant energy consumption burdens operation expenses, especially for huge cloud computing companies such as AWS, Google Cloud, and Microsoft Azure, which host a vast data center infrastructure across the country [4]. This has been made possible by the increased use of data-intensive applications in streaming services and artificial intelligence (A.I.). Cooling, most significantly, accounts for 30-40 percent of energy consumption in some U.S. data centers [5].

Minimizing energy costs and usage has made companies look for more efficient cooling techniques and enhanced server utilization policies. Consequently, liquid cooling systems and such modular data center designs have emerged as popular due to their high cooling efficiency, according to workloads. For instance, the concept of the modular data center involves the construction of the data centers in one or multiple smaller and standardized sections, making it possible to scale and cool them depending on operational requirements. The states have also contributed to regulating energy consumption through incentives, with some of the states in the United States encouraging the utilization of renewable energy or incorporation of energy efficiency in data center operations [6]. In addition, the federal and state governments have also adopted some measures to drive the shift to environmentally friendly data centers. This includes the promotion of renewable power sources and the establishment of goals for energy efficiency measures. As a result, the data centers have found it necessary to use embodiments from renewable power sources, including wind and solar power, to minimize their impacts on power grids [1]. They dovetail with concerns for sustainability in broader terms and are part of the growing tendency to reduce the earth's digital footprint.
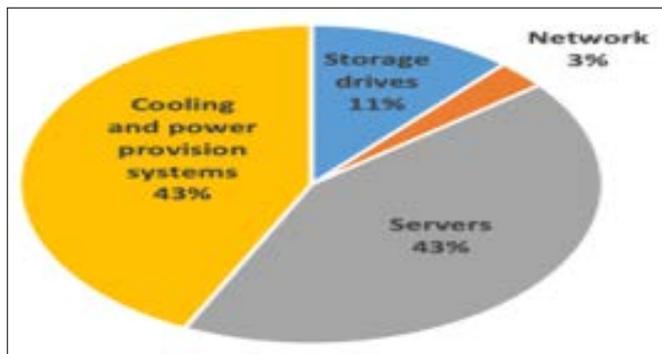

Figure 3: Energy Do Data Centers Really Use

Carbon Emissions and the Carbon Footprint of Data Centers
Nowadays, data centers are an essential component of information and communication technology, and they offer services ranging from cloud computing to artificial intelligence. Although they use large amounts of energy, they are relatively new sources of pollution since they release much carbon. This section looks into the world's CO2 emissions from data centers, initiatives by key cloud operators to minimize their emission impacts, and the impact of energy type on emissions.

Global CO2 Emissions from Data Centers
To compensate for the high energy requirements of the data centers, emissions to the atmosphere are high, contributing to most of the carbon output. Data centers contribute to approximately 100 cross million metric tons of CO2 emissions annually, or about 0.3% of the global total emissions in 2018 [7]. Even though this value may seem average, it represents a rather significant environmental issue, especially as the demand for digital services continues to grow exponentially alongside the shifting trend towards cloud computing. Power consumption occurs mainly through server activities, cooling systems, and networking devices, and nearly

all data centers utilize energy resources that contribute to carbon emissions. Accordingly, data centers are less impactful than other industries; transport industries account for roughly 14% of global CO2 emissions, while manufacturing industries emit about 22%. However, emissions generated by data centers are likely to rise as organizations embrace digital transformation strategies, something that calls for change to be made. The trend of emissions relative to data centers mainly depends on various variables, including the data processing load that results from the expansion of AI applications and increased internet activity [8]. The ever-rising complexities of computation, analyzed through technology such as blockchain and machine learning algorithms, compound the problem, increasing the importance of sustainable practices in data centers.

Case Studies: Major Cloud Service Providers
The major CSPs have also made great strides to reduce emissions by procuring renewable electricity and enhancing energy usage. For instance, Google was the first key cloud service provider to complete its 2017 energy requirements matching the global level and buy as much renewable energy as its consumption rate. This was made possible due to investments made by the company in its wind and solar power generation, which would cancel out the power used by the data centers. Further, Google has incorporated AI in its cooling system in its data centers, whereby nearly thirty percent of the energy used for cooling has been cut [9]. At Amazon Web Services (AWS), executives have also made sustainability a top policy goal by aspiring to obtain all its power from renewable sources by 2025. AWS stated that approximately half of all its data centers' electricity is sourced from renewable energy. Thus, Amazon has bought wind and solar energy worldwide and has achieved growth in renewable power capacity. The company has also implemented servers and infrastructure improvements to increase energy use efficiency and cut down the energy intensity of data centers.

Another critical participant, Microsoft, declared to be a carbon-negative company by 2030, aiming to eliminate more carbon than it expels. The organization has made progress in decreasing carbon emissions by obtaining renewable energy and energy-efficient technologies in its data centers. Google's efforts include integrating pre-fabricated modular facilities and Artificial Intelligence based cooling systems. Microsoft's efforts are similar to Google's regarding efficient energy use by designing the data centers. All these measures placed the company as the market leader in sustainable cloud services within the cloud services market. The measures these companies have adopted show that data centers can achieve colossal carbon footprint reduction through investment in renewable energy and embracing technological advancement. However, while the main CSPs have had meaningful improvements, small data centers and co-location amenities make it challenging to adopt comparable tactics due to budget and workforce constraints [10]. Such a division raises the issue of industry-wide cooperation and state encouragement of sustainable initiatives for all stakeholders.

Impact of Energy Sources on Carbon Emissions
The energy sources used to fuel data centers are a significant factor in the carbon footprints of such data centers. Most co-located data centers have more significant emission rates as most electricity originates from coal and natural gas compared to renewable power. For example, data centers in countries like China and India, where coal power is still widely prevalent, have far higher carbon footprints than in places like Sweden and Norway, where hydropower and wind energy dominate. Using

fossil power, in addition to contributing to an elevated level of carbon emissions, puts the data centers at risk of regulatory hazard due to governments enhancing their environmental standards. On the other hand, using clean energy and efficient technologies like wind, solar, and hydropower has been identified as a feasible approach to minimizing the carbon dependence of data centers. Renewable energy integration can reduce the carbon intensity in data centers by substituting CO2-emitting electricity with clean power [11]. This strategy has been most successful in locations with cheap and extensive renewable resources where the energy cost for data centers is decreased. However, the impact on the environment is low. However, using renewable energy resources is volatile for continuous power supply. Hence, renewable power is needed to complement storage systems or backup power.
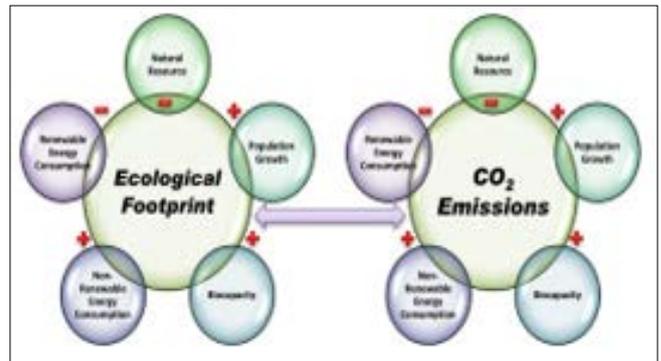

Figure 4: The Impact of Natural Resources, Energy Consumption and Population Growth on Environmental Quality

Power Usage Effectiveness (PUE) remains one of the most well-known indicators of a data center's efficiency and is affected by the energy mix. Energy efficiency is closer to scope, measured by power usage effectiveness or PUE, where a lower number is preferable, and it can be driven by clean energy and cooling technologies, among others. Such data centers tend to have better PUE values since the integration of renewable energy is a partnership between clean energy production and consumption and energy efficiency enhancement [7]. As a result, the funding for renewable energy cuts the carbon emission level while increasing the efficiency of data centers. The carbon emission problem is linked most directly to the type of energy employed to generate electric power for the data center. New energy sources have taken a pole position in reducing the social world, with the overall cloud providing services on the front line. Nevertheless, how many smaller data centers can afford to go green or how can they organize themselves to do so becomes a question. This underlines the need for policy backing and encouragement to ensure the utilization of low-carbon electricity in the power industry.

Taxing CO2 and Carbon Regulations for Data Centers
Introduction to Carbon Taxation
Carbon dioxide taxation, commonly known as Carbon pricing, is another policy instrument in which fees are charged to firms relative to the amount of CO2 they emit. The underlying objective of this tax is to encourage firms to minimize their emissions through clean technologies or by moving to cleaner sources of energy [12]. CO2 taxes are thus significant to data centers that use much energy, as they directly impact overall expenditure strategies. Because data centers are at the heart of computer systems that support cloud computing services, social networking, and artificial intelligence, all the energy used is consumed in the form of enormous amounts of electricity, which, when sourced from traditional fossil fuels, contributes significantly to carbon emissions.

The goal of the CO2 tax is to make these emissions costly, especially for firms, to force them to switch to renewable energy or come up with new efficient ways of cutting energy use. CO2 taxation imputes the environmental cost of carbon emission on the data center, implying economic pressure to conserve energy and reduce emissions. It also assists in creating a legal regulation for taxing to support investments in renewable energy sources that are favorable to the concerns of data centers. Further, carbon taxes make efficient and innovative cooling solutions and server management a possibility that can reduce the general impact of data centers by a great deal.

Application of Carbon Taxes in Different Regions
European Union (EU)
The EU has pioneered carbon pricing instruments, including the Emission Trading System, which began in 2005. This system uses the cap-and-trade form in which organizations such as data centers purchase allowances to emit a specific quantity of CO2 [13]. The cap is slowly reduced, which means allowances become more costly for businesses and companies by periods, which creates a financial disincentive for organizations to emit excessive amounts of carbon. Due to the EU ETS, European data centers have been forced to adopt green energy technologies and efficient processes like AI cooling technology.
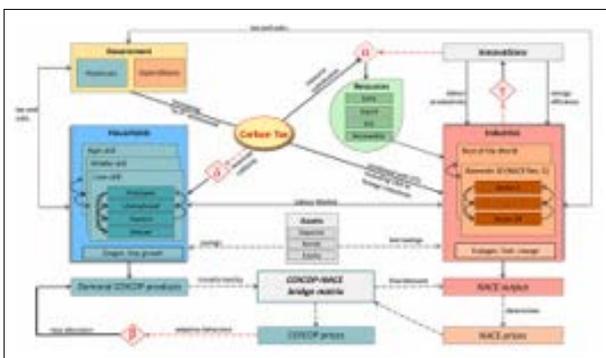

Figure 5: Introduction of the Carbon Tax in Italy

Even facilities outside the EU ETS regulation, such as large-scale data centers, are still in the woods since they are under regional taxes and sustainability measures [14]. Investments in renewable energy have caused many data centers across Europe to adopt wind and solar energy. For instance, Microsoft and Google have stepped up efforts to find ways to buy power from renewable sources to reduce carbon emissions. Additionally, initiatives such as the "Green Data Center" program in the EU have set high energy efficiency goals for data centers, encouraging less energy usage.

Canada
Carbon pricing is done at national and state levels, with the national government putting a minimum price check on carbon emissions. Data centers have been recognized as Level 3 large industrial emitters and must meet a carbon tax depending on the volumes of CO2 emitted. The implemented federal carbon tax is at CAD 40 per metric ton of CO2, with annual increments intending to reach CAD 170 by 2030. The low pricing encourages data centers to use renewable power and to integrate efficient technologies such as free-air cooling.

Companies running data centers in Canada have thought of ways of reducing emissions. Some notable examples of such offsets are the vast hydroelectric power available in the country to light up the data centers with the most diminutive carbon footprint. Furthermore, the adoption of AI for managing energy consumption is gaining traction as organizations look for ways to offset the increased cost of carbon taxes [15]. The case of Canada, which offers federal and provincial-level regulatory policies, is a constantly evolving environment for data center development.

United States
The present study also needs evidence of a federal carbon tax in the U.S. Certain states, like California, have introduced regional cap-and-trade measures [16]. California's program is quite similar to the EU ETS because it puts an overall limit on emissions and makes companies purchase allowances for any emissions over the limit. This regulatory environment indirectly affects data center operations by promoting energy utilization to increase efficiency and the use of renewable energy. Many large technology firms with data centers in the United States have pledged to adopt 100% renewable power partly because of state-level directives.

Leading firms in the United States, such as Amazon Web Services (AWS) and Google, have invested hugely in procuring solar and wind energy to support sustainability initiatives [7]. Additionally, corporations' CSR activities have emerged because companies understand that unplanned emission reductions can minimize regulatory uncertainty and respond to clients' green consciousness. While the policies on carbon pricing are not standardized at the federal level, the state policies establish a fragmented but rising stringency that directs the data centers to become environmentally friendly.

Carbon Footprint Metrics and PUE
Measurement of carbon footprints and Power Usage Effectiveness (PUE) are valuable indicators concerning the data center's environmental impact. PUE quantifies the use of power in the facility by comparing the total power used in the power distribution to the power used by IT load only. Ideally, the PUE should equal 1.0, indicating that all power consumed is put to productive use within computation work, and none is spent on cooling or lighting. Nonetheless, actual data centers establish a 1.5-2.0 PUE depending on technologies and cooling systems.

By sourcing energy from renewable energy sources, giant data centers can significantly enhance PUE because the energy required for cooling takes a significant share [12]. While PUE gives only the efficiency of energy used in the data center, carbon footprint analysis also includes the emissions that the data center contributes to the environment based on the nature of the energy that is being used and the carbon intensity of the energy source in the geographic location of the data center. The carbon impact on data centers located in regions with rich renewable energy sources is lower than for those dependent on coal or natural gas. Moreover, the carbon intensity indicators are embedded into the data centers with energy management systems that optimize energy usage to decrease emissions [17]. Like PUE, the carbon footprint data allows for describing issues and adopting best practices within a data center. The environmental impact can be cut in half while adhering to regional carbon legislation to achieve proper cooling and implement new renewable energy sources. Hence, these metrics come in handy and assist data centers in achieving sustainable operations.

Table 2: Summary of Carbon Taxation and Carbon Regulations for Data Centers across Different Regions

Aspect	Details
Introduction to Carbon Taxation	- CO2 taxation charges companies for carbon emissions to incentivize cleaner energy use and energy efficiency. - Encourages investments in renewable energy and adoption of energy-efficient technologies.
European Union (EU)	- Uses the Emissions Trading System (EU ETS), a cap-and-trade model that requires companies to buy allowances for carbon emissions. - Encourages renewable energy adoption and energy-efficient technologies in data centers.
Canada	- Federal and provincial carbon pricing, with a federal carbon tax reaching CAD $170 per metric ton by 2030 - Incentivizes data centers to adopt hydroelectric power and AI-based energy optimization
United States	- No federal carbon tax; regional initiatives like California's cap-and-trade program impact data centers. - Major data centers are investing in renewable energy (e.g., solar, wind) to meet state-level regulations and CSR goals.
Carbon Footprint Metrics and PUE	- PUE measures energy efficiency as a ratio of total facility energy to IT equipment energy. Ideal PUE is 1.0, but real-world data centers often range from 1.5 to 2.0 - Carbon footprint analysis assesses emissions based on local energy grid composition.

Strategies to Reduce the Carbon Footprint of Data Centers

The ever-increasing energy consumption of data centers has put their impact on the environment in the spotlight, and the need for the stakeholders to look for new methods to employ in reducing the impacts of their energy consumption is felt. This section explores general approaches such as transitioning to renewable energy sources, employing technology, and experimenting with modular, AI-based approaches. Further, new practices for the future and sustainable data centers are named.
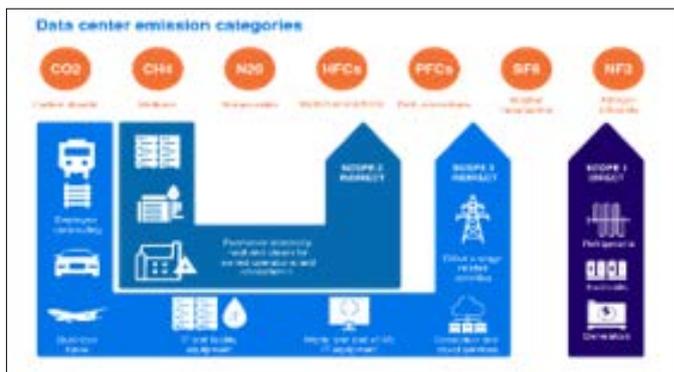

Figure 6: Data Center Carbon Footprint

Adoption of Renewable Energy

Large-scale corporations are switching to using green power in computer centers due to efforts to minimize the environmental impact of data centers. This transition is largely achieved by using energy from renewable resources such as solar, wind, or hydropower to reduce the consumption of electrical energy from conventional carbon-based systems. Renewable energy does decrease carbon emissions but also aids in the longevity of cost-effective measures for data center owners [18].

A clear example in this respect has been seen through most cloud service providers' procurement of renewable energy certificates and direct investments in RE projects. For instance, companies such as Google opt to balance 100% of the electricity being used with renewable energy purchases, substantially lowering its overall carbon footprint [19]. These activities indicate that ensuring that renewables form the basis of electricity generation in large data centers is transferable. Other small data centers can follow suit. However, the shift to renewable energy sources must be completed with various challenges. Fluctuations in the availability of solar and wind resources require a reliable energy storage mechanism, especially for data centers. Energy storage is essential in determining the reliability of data center operations during low production of renewable energy success; developing efficient battery storage systems is crucial. Both these initiatives of procuring renewable energy and investing in energy storage industries can be instrumental in de-carbonizing the data centers.

In addition, location is a critical factor in determining the use of renewable energy in data centers. Plants in areas with good renewable energy sources, like the southwest of the USA or some parts of northern Europe, will benefit more from solar and wind resources. With the help of placing new data centers where renewable energy share is high, more clean energy will be incorporated, and the emissions will be cut even deeper [20].

Technological Innovations for Energy Efficiency

An0ther than renewable energy sources, technological factors have immensely boosted energy efficiency in data centers. Such innovations are AI-empowered cooling, virtual computing, and modularity in data center designs to decrease energy usage and emissions. Automated cooling systems have been confirmed as one of the most efficient methods to minimize the energy used to maintain proper working temperatures for data centers. These systems can learn and adapt cooling based on actual data about the servers' load temperature and humidity levels in the room. Google's artificial intelligence cooling system has been claimed to cut energy consumption by a third, showing how AI technology aims to make data centers more efficient. This not only saves energy costs but also reduces the ecological impact of using air-cooled methods instead of water-cooled methods.

The other technological advancement involves virtualization, which runs several operations on a single physical hardware device. This move has revolutionized energy consumption in data centers. Server and inflation rates in the industry are thus lowered by virtualization due to the fewer number of servers required to be powered and cooled. Shehabi et al, noted that studies have found that virtualization can help cut energy consumption in data centers by up to 40%, making it a key driver of energy efficiency measures [10]. Also, the modular data center concept has attracted interest as a flexible and efficient way of deploying data centers. These designs make it possible to efficiently scale up or down the server capacity using energy depending on current or future usage. Another advantage of modular data centers is that they are often equipped with the best cooling mechanisms and power control systems, making them more efficient in energy usage [20]. The modularity aspect also enables a faster rollout of the new architecture and a faster scaling depending on the computation required.
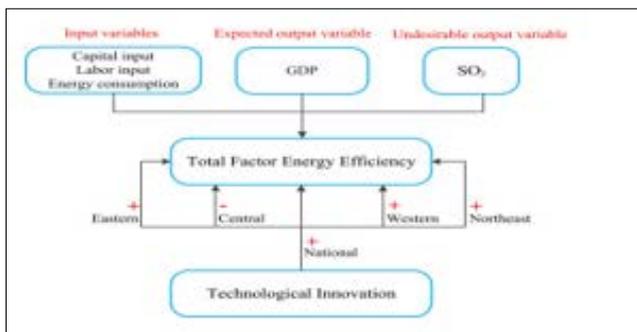

Figure 7: Effects of Technological Innovation on Energy Efficiency

Impact of Modular and AI-Driven Data Centers
The adoption of modularity designs and artificial intelligence has seen various data centers record huge strides in energy efficiency, and the various case studies depict this. A case in point is using mobile data centers developed by Microsoft, which could decrease energy consumption by about 25% more than stationary data centers. These modular facilities incorporate efficient liquid cooling systems that consume less energy than entrenched air-cooling techniques and assist the data centers in reducing their carbon impacts. Another example is the application of AI cooling in Alibaba data centers in China. Using Machine learning, the company was able to adjust the cooling parameters and the flow rate of the cooling system and thus experienced a decrease in the energy consumption for cooling by 15 % throughout their buildings. This case study also highlights the ability to scale up AI-based cooling solutions, which can be implemented across micro data centers regional, and global data centers.

Modular designs have also been useful in the edge data center market, which involves localized compute infrastructure near the data source. These facilities consume less energy than the monolithic hyperscale facility type but still need cooling and power infrastructure. The ability to scale capacity at the edge using modular solutions has a lower energy footprint and can help make the data center more sustainable [19]. We must recognize the advantages of these innovations in reducing energy consumption, cost, and reliability. In light of trimming the energy usage for cooling and IT use, data centers can reduce operational costs, thus channeling more resources towards additional sustainable measures. Such systems can tell beforehand that a certain part is likely to become a source of trouble and help avoid disruptions.

Future Trends in Data Center Sustainability
Several trends and innovations define the future of data center sustainability and its capability of cutting carbon emissions and increasing energy efficiency. Among them are liquid cooling, energy optimization, and renewable energy infrastructure within the data center. Water cooling systems where a liquid provides cooling for servers gradually replace air cooling as the more effective method. Liquid cooling systems have a higher heat capacity and relatively produce less energy for heat exchange, thus leading to energy efficiency benefits. Liquid cooling cuts data center cooling power use by a third or even half of that associated with conventional cooling techniques. This, in turn, makes it a preferred choice for data centers seeking to increase their sustainability. Besides liquid cooling, electronic hardware with efficiency as an integrated factor is widely expected to hold the key to cutting data center carbon emissions. Software developers focus more on efficient, specialized ASICs and GPUs, which consume less energy when resolving specific tasks. According to Wang and Preininger. AI Hardware Improvements using Healthcare Informatics can enhance the computational capacity of data centers, leading to increased workflow within the same power footprint as before [21].

Figure 8: Prediction of Emerging Data Center Trends by 2022

Another trend here is the combination of local renewable energy sources like solar panels or wind turbines mounted in the data center. Renewable resources can be installed within or close to data facility locations at a smaller scale than the overall required capacity, and they help decrease dependence on the grid, where the energy mix is predominantly carbon-based. These renewable energy could be generated within the data center premises and serve as the backup in case of power blackouts, possibly improving the dependability of data center operations. This strategy aligns with the general movement to decentralize power generation to support the sustainable development paradigm. Carbon offset programs are expected to rise due to the rising demand for data centers that want to achieve a net-zero carbon footprint [22]. These include buying or sponsoring carbon credits sourced from environmentally friendly projects like afforestation or developing renewable energy sources that can balance the greenhouse gas emissions made by data centers. Carbon offsets are not the solution to the data center carbon issue but are a useful supplement to energy efficiency initiatives.

Measuring the Amount of Environmental Change
Data centers are environmentally sensitive, especially from the carbon footprint that arises from their high energy use. Currently, it is possible to calculate the emissions from data centers where metrics such as CO2 emissions per TWh and an energy mix analysis provide information concerning the total emissions from the energy used and the origin of that energy.

CO2 Emissions per TWh

The overall emissions from data centers are inextricably linked to the main network's energy supply mix. This means that emissions per TWh can fluctuate tremendously depending on which end of the generation spectrum of a grid is drawn from fossil fuels or renewable energy. For example, energy grids that rely heavily on coal or natural gas have more emissions because carbonaceous fuels release much CO2 from combustion. However, the states where renewable power like wind, solar, and water supply a significant amount of energy at a TWh rate have low emissions. Research conducted by Jones in 2018 revealed that data centers operating in the regions that relied on coal had a carbon intensity up to five times that of regions with cleaner energy sources. This is how the energy grid composition influences the data centers' carbon footprint, as the amount of CO2 emitted per energy consumed depends on it.

Data centers based in areas where governments have sought to adopt measures to Curtail the use of fossil fuels are likely to have a lower CO2 per TWH emission level [23]. For instance, the European countries that have invested much in renewable energy sources have realized lower carbon intensity. The decision to use intelligent cooling and the modular concept of data centers also decreases energy consumption and respective emissions [24]. Hence, obtaining the CO2 emissions per TWh is crucial as a yardstick for measuring the polluting nature of data centers and can contribute to future improvements.

Energy Analysis Its Pertinence

Energy mix review studies the distribution of different energy types utilized in data centers, especially concerning renewable energy and its share with fossil fuel energies. This analysis is useful in quantifying the carbon footprint since it reveals the percentage contribution of low-carbon energy. There is substantial evidence that the global carbon footprint is lower when more renewable resources are utilized to produce energy. Rising renewable energy contributions decrease the CO2 emissions of data centers even if the power usage escalates.

Figure 9: Analyzing Energy Flows Within Industries

Regional energy policies greatly affect the energy supply and, in turn, shape the data centers' environmental footprint. Those countries that have set themselves a low-carbon diet or are signatories to such agreements, especially in the European Union, have directed their efforts toward achieving cleaner data emissions. On the other hand, some regions with no clear energy policies in place may, therefore, keep using carbonaceous electrical networks to feed their technologies while increasing efficiency, thus the carbon impact [25]. Globally, as data center capacity increases, there is a need to increase the share of renewables in the energy mix to cut emissions and meet climate goals. The assessment of the energy mix is crucial in developing policies that promote the use of renewable energy and the less generalized impact of data centers. It offers insights into how emission rates relate to an energy source's proportions and

enables the formulation of policy measures to influence specific sectors [26,27].

Conclusion

Business data centers facilitate today's more connected and advanced digital environment and emerging trends such as the cloud, AI, and data centers. Still, they consume much energy, impacting the environment, such as carbon emissions. Energy consumed by data centers was approximately 200 TWh in 2018, and thus, the data center's contribution to the global carbon emission is 0.3%. These emissions are associated mostly with fossil fuel-based energy systems, further underlining the issue of sustainable energy. Despite recent innovations that have helped to constrain data center power requirements, the topic's impact on the natural environment is still a major issue due to the ever-increasing uptake of digital services.

Initiatives to protect the effects of data facilities have included energy constitution and technology escalation. Large CSPs such as Google, AWS, and Microsoft have exhibited certain levels of improvement and shifts to cleaner sources of energy and more energy-efficient technologies. Smart cooling techniques and virtualization have proved to be effective measures in reducing energy use and have provided some directions toward achieving sustainability. However, there still needs to be a clear divide as the small data centers cannot compete with the big players and implement sustainable methods.

They are imposing a carbon usage fee, which is seen here as a way to mitigate this effect on the environment of data centers. Carbon taxes and similar rules, such as the Emissions Trading System for the European Union and regional carbon prices for countries like Canada, press data centers to reduce emissions. These policies put a price tag on carbon, thus encouraging the use of more renewable resources and improving efficiency. However, there are still problems in adopting standardized rules in different regions because different policies cause different effects on data centers.

The plans for data center development include further changes in the use of renewable energy and additional optimization. Wind, solar, and hydropower are the essential solution opportunities that can minimize data centers' carbon intensity. However, the transition to renewables to address the problems of power generation and supply comes with difficulties, such as storage. Technologies like AI cooling and modularity in data centers are important for energy. They must meet the demand for various services as clients gain more access to digital services. Also, there could be synergies between policymakers and industry stakeholders in developing standards to encourage sustainable practices in the data center industry.

Despite the efforts made in recent years, promoting further development of the digital industry without simultaneously burdening the environment remains a difficult challenge. To mitigate the sector's direct environmental impact, more funds are needed to capitalize on renewable energy and efficiency technologies. Also, increasing carbon rules and promises and providing rewards for reducing carbon emissions will help make data centers more environmentally friendly. Data centers in the digital economy are absolutely critical, as is ensuring their global compliance with climate targets.

Data centers must serve to meet the various demands for digital services in reducing the impact on the environment. With advanced technologies, the usage of renewable energy, and favorable policies, the industry can strive to minimize the negative impact of data centers in decades of digital change. As the world advances in the digital frontier, future plans and efforts to make data centers more

environmentally friendly will continue to be instrumental towards a sustainable economy in the foreseeable future.

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