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Data Centers and Green Energy: Paving the Way for a Sustainable Digital Future

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Abstract: As Information and Communication Technologies (ICTs) reach unprecedented heights of global influence, the USA stands as a leader with 91.8% of its residents connected to the internet. The interconnection of sectors like healthcare, finance, social media, and governance through the internet results in an immense volume of data, stored and managed globally within Data Centers. The surge in Data Centers in the USA, driven by a 4.12% CAGR and expanding service providers, prompts a critical examination of their environmental impact. Currently, nearly 2% of the USA's total energy production is attributed to Data Centers, predominantly reliant on conventional energy sources. This research explores the potential transition of Data Centers to green energy sources, investigating the feasibility of taking them off the grid. By aligning internet user growth, Data Center functionalities, and the USA's renewable energy capacity, the study aims to unravel the environmental implications and sustainability challenges faced by the Data Center industry. Through an in-depth analysis of key point indicators for Data Center sustainability and leveraging various renewable resources, the research assesses the viability of supporting Data Centers with green energy in the USA. The findings delve into predictions for renewable energy production, offering insights into aligning energy consumption patterns with sustainable practices for a greener digital future.

Keywords: ICT, Data Centers, Internet Usage, Environmental Impact, Sustainability, Renewable Energy, Green Energy, USA, Energy Consumption, Key Point Indicators, Green Data Centers, Sustainable Practices, CAGR, Energy Transition, Digital Future.

I. Introduction

ICTs, or Information and Communication Technologies, have significantly altered the world. More than 50% of the world's population is connected via the internet as digitalization approaches its peak. With 91.8% of its residents, the USA is one of the countries with the highest number of internet users (World Bank, https://datareportal.com/reports/digital-2023-global-overview-report). Sectors such as healthcare, banking, social media, networks, marketing, legislation, governance, and environmental services are interconnected through the internet. Every piece of information, whether in the form of a picture, document, sensor-generated data, controller program, software output, etc., is converted into binary ("Data") and stored for future retrieval and processing. Globally, Data Centers provide the space for managing all these activities.

A Data Center is a place that offers computing, storage, and networking services to store, manage, and transfer data to/from any user/individual worldwide. Both the service provider and end-user utilize the Data Center in one way or another. The increase in user numbers, data generation, and storage capacities has led to the requirement for more efficient Data Centers to improve data storage facilities for metadata (redundant, black data, critical data). As a leader in the field, there has been a steep increase in the number of Data Centers observed in the USA in the past decade. Nearly 2% of the total energy production of the USA is dedicated to the environmental impact analysis of Data Centers, making it a necessity. A Data Center is established using servers, networking cables, and cooling tower-like facilities. With the proposed growth of 4.12% CAGR in the USA, increased Data Center service providers, and growing capacities, there is a critical question of evaluating the environmental impact of the Data Center industry. Most Data Centers in the USA are plugged into municipal electrical grids for their power supply and rely on diesel-based power generation in times of emergency (Shehabi, 2018). This dependence on conventional energy sources makes addressing not only the environmental impact but also making them sustainable a challenge for the coming days in the USA and the world. With an increase in green energy production using solar, wind, and hydrothermal sources, there is a possibility of taking Data Centers off the grid and making them self-reliant.

The available literature contains scattered data on the increase in internet users, the growth of Data Centers, the current capacity of the USA for renewable energy production, and the energy requirement by Data Centers. This research aims to correlate the available data and evaluate the possibility of supporting Data Centers with green energy in the USA. The research article introduces readers to the overall view of Data Centers (data usage, functionalities of Data Centers, and Data Center growth in the USA) and their possible environmental impact. To address this issue in detail, we then delve into details on key point indicators

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for Data Center sustainability and types of renewable resources the USA can leverage to compensate for the power needs of Data Centers. It presents predictions for renewable energy production over a period and overlaps with energy consumption patterns.

II. Methodology

With a review-based approach, this research data analysis contains extrapolated data based on the trends observed via regression analysis for an increase in the internet user's data. The historical data has been procured from various data sources. The data collection has been processed by manual searches and data downloads from original data sources (Government sources, archived websites, and research paper supplementary information) and has been used to visualize energy consumption trends by Data Center and projection of renewable energy production trends. The statistical analysis and data representation have been conducted using the software MATLAB with second order polynomial fit (https://www.wolframalpha.com/input/?i=fit+polynomial&f1=%7B1%2C+4%2C+9%2C+16%7D&f=InterpolatingPolynomialCalculator.data%5Cu005f%7B1%2C+4%2C+9%2C+16%7D&a=*FVarOpt-_**InterpolatingPolynomialCalculator.data2).

III. Data usage and functions of Data Centers

The production of data has steadily evolved from 1.2 zettabytes in 2010 to approximately 59 zettabytes in 2020. This includes the annual amount of data produced, predicted to increase from the said 35 zettabytes in 2010 to a projected 175 zettabytes by 2025. More data is being created, necessitating more storage and processing power, which in turn leads to a demand for more Data Centers (Daigle, 2021). In the chart shown below, we see the rise of internet users in the USA, UK, India, China and total world (World) from the year 1990 onwards. The estimated increase rate for internet users is estimated to be ~7,656,913 users per year considering the growth rate from the year 2000.

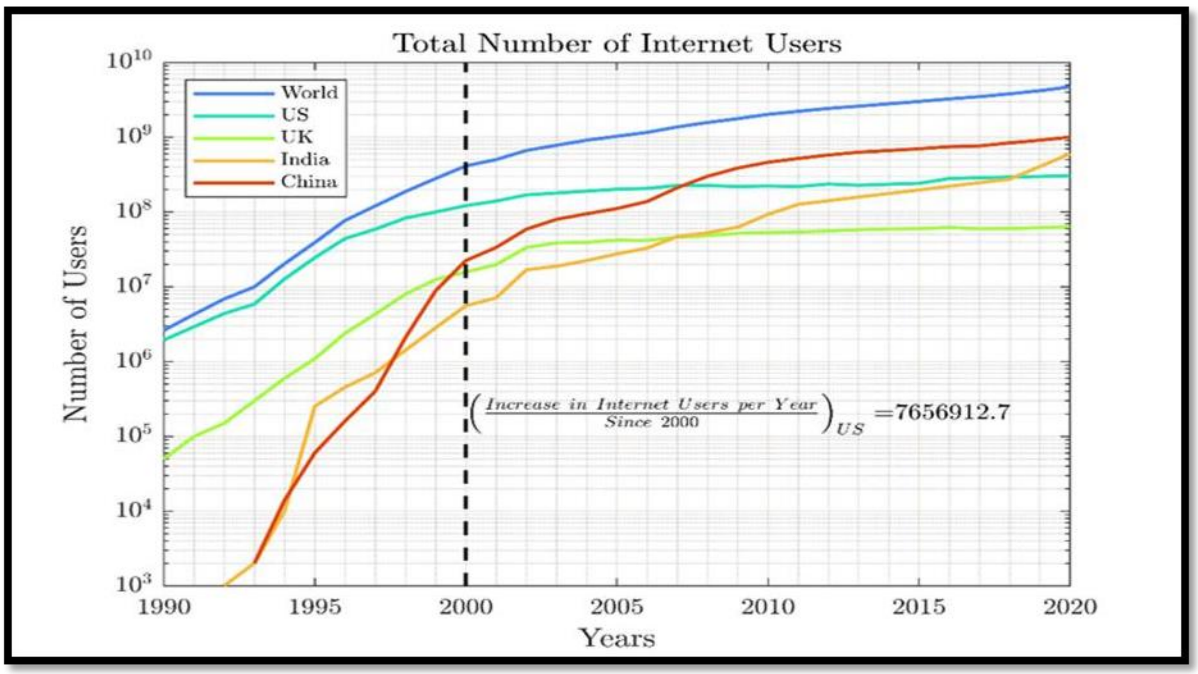

Figure 1: Number of internet user (world, US, UK, India, China) and rate of expected rise of users (US) (https://ourworldindata.org/internet)

More than 50% of the world's population uses Information and Communication Technology (ICT) (World Bank, https://datareportal.com/reports/digital-2023-global-overview-report)-related services in today's world, and Data Centers (DC) play a crucial role by serving as the nodes or spinal nerve centers for various digital services and applications.

The rise of tech giants in the USA has initiated improved integration of the data-driven economy with urban communities globally. Data also suggests that more than 90% of the U.S. population are ICT users on one or more devices (World Bank, https://datareportal.com/reports/digital-2023-global-overview-report). The need for efficient data management to serve people and a growing market in the USA is reflected by the presence of 42.6% (2,701 out of 6,334) Data Centers in the world (Figure 2).

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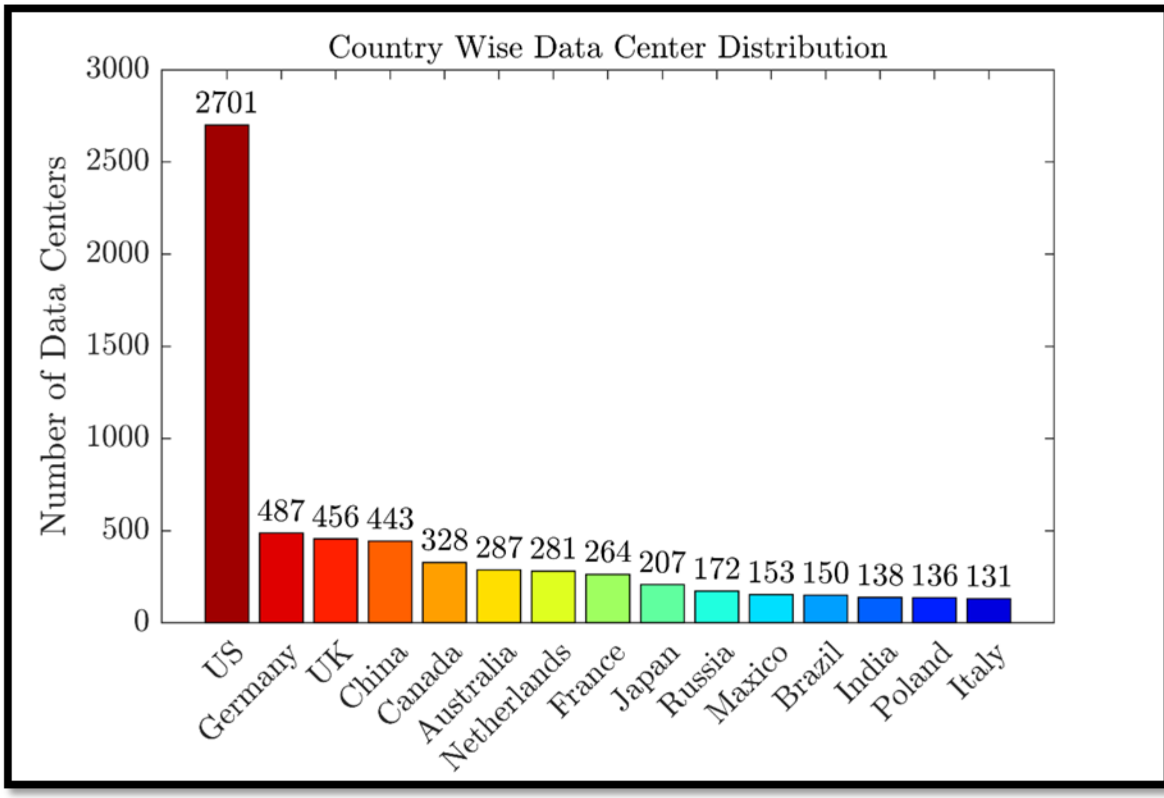

Figure 2: Number of data centers in the world: Country wise Data Center Distribution. (https://techjury.net/blog/data-center-statistics/)

The overall growth of the sector has increased from $298.3 billion (in 2020) to $342.10 billion in 2023, and it is predicted to grow at a CAGR of 4.12% in the US. Being one of the largest Data Center markets in the world (https://www.statista.com/statistics/1228433/data-centers-worldwide-by-country/), it also makes them responsible for navigating the world towards a sustainable future in the ICT segment with technological advancement.

From a functionality perspective, a Data Center's primary function is to manage user interactions with server-based software tools and web portals. The architecture of Data Centers can vary, being on-premises, cloud-based, or a hybrid of the two, depending on business needs. The categorization of data centers depends on factors such as services, outputs, and architecture.

- Managed service data centers
- Colocation data centers
- Cloud data centers
- Hyperscale data centers

It is often stated that a Data Center is more than just IT equipment; it encompasses various components beyond computing machinery. Typically, a Data Center includes essential hardware and software for data security, computing, storage, networking, and cooling. Each of these categories forms the backbone of a Data Center and is supported by corresponding hardware and software.

- **Security:** A Data Center safeguards an enormous amount of data from individuals, nations, healthcare entities, and global social media giants. Preserving the integrity and safety of this data is paramount. Therefore, a critical aspect of Data Center infrastructure involves dedicated software and firewall infrastructure to ensure its security.
- **Computing - Servers:** The heart of a Data Center lies in the computational services provided by servers. These servers are often arranged in racks or stacks to optimize space. Various types, such as blade and tower servers, are utilized in Data Centers, and their structures continue to evolve with advancements in technology.

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- **Networking:** Maintaining connectivity to the internet is crucial for the servers in a Data Center. This is achieved by placing them in common network channels. Routers, network switches, and integration cabling contribute significantly to the polymer and metal utilization within the Data Center.
- **Data storage:** Various storage solutions such as NAS (Network Attached Storage), DAS (Direct Attached Storage), Solid State Drives (SSDs), Flash arrays, and tape storage are typically employed within a Data Center for efficient data storage.
- **Data Center cooling:** Computer room air conditioners (CRAs) are used to maintain optimal temperatures in server rooms and prevent overheating. Data Centers are equipped with HVAC systems to control environmental parameters such as humidity and heat exchanges. AI tools are also utilized to support human efforts by monitoring parametric data.
- **Power/electricity connections:** The effectiveness of a Data Center is often measured by its downtime and uptime. A stable electrical supply is essential for running computer systems and maintaining the Data Center's global network connection. Data Centers typically draw electricity from the municipal power grid, making them reliant on the town/city's power source. Additionally, all Data Centers have electricity generators powered by diesel in case of power failures. To further ensure uninterrupted operation, Data Centers are equipped with power backup systems, such as Uninterruptible Power Supplies (UPS).

Apart from the primary classification according to the functionality of the Data Center; the Data Centers are classified based on the efficiency of services, downtime, and server specifications. The other well-known categories are Tier I, II, III, and IV based on the data management capacities. Focusing on US-based Data Centers, the following map (Figure 3) of the USA indicates the presence of several Data Centers in the states of the USA.

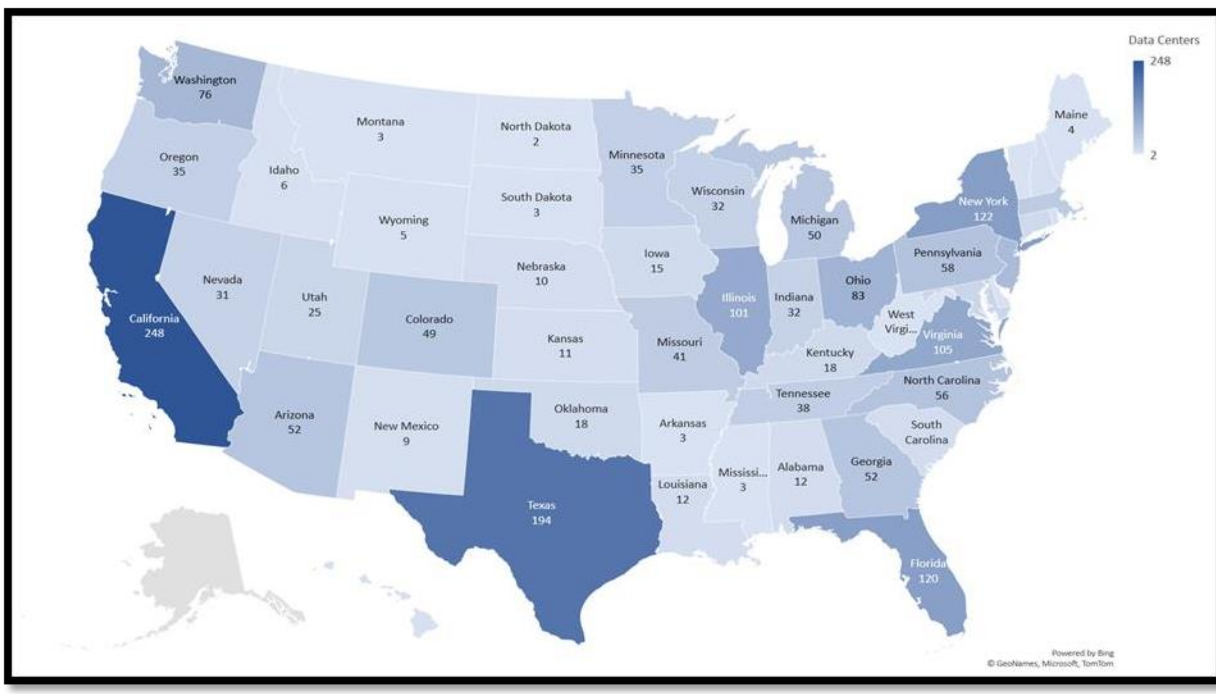

Figure 3: Number of Data Centers in USA (State-wise) https://www.datacentermap.com/usa/

With the highest number of Data Centers, California and Texas are the focal points of Data Center facilities in the US. The other states are less dense in terms of Data Center presence.

Besides the private network of Data Centers, the USA also houses several federal government Data Centers for government-specific ICT services. In order to address the energy consumption and proliferation of federal Data Centers, the government has introduced an initiative known as the 'Data Center Optimization Initiative (DCOI),' as part of the Federal Information Technology Acquisition Reform Act (FITARA) in 2014 (source: https://datacenters.lbl.gov/federal-data-centers). The surge in ICT service users and providers has triggered a revolution for improved services and connectivity to the public, but it comes with a cost. The

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construction of such large structures to house a massive number of servers and ancillary equipment requires land, energy to power the servers, and water for the cooling equipment. Figure 4 illustrates the breakdown of energy consumption across various functionalities of DCs (Dayarathana, 2017). It is evident that the cooling equipment accounts for nearly 50% of the total energy consumed, followed by 26%, 11%, and 10% for servers and storage, power conversion, and networking utilities.

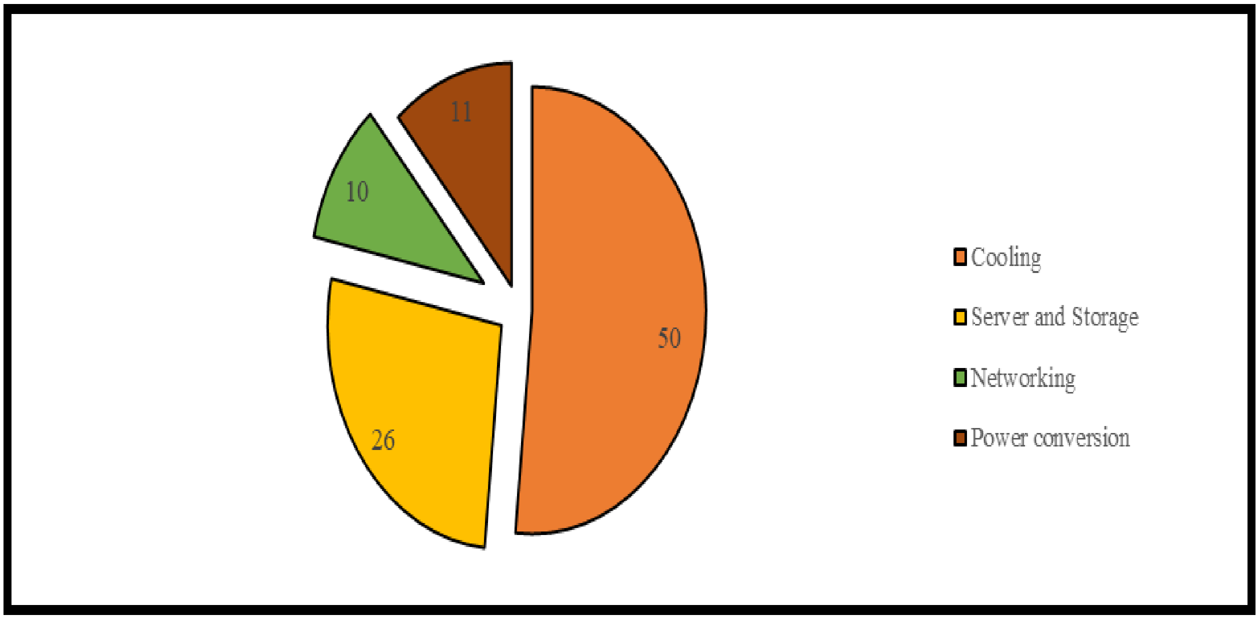

Figure 4: Breakdown of energy consumption in a data center (Dayarathana, 2017)

To ensure the functionality of Data Centers, essential infrastructure such as HVAC systems, fire suppression systems, redundant/backup power supplies, redundant internet connections, and high-security systems is required (source: https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/data_center.pdf). These necessities not only contribute to a substantial financial investment but also impose costs on the environment by consuming valuable resources. The United Nations (UN) established 17 objectives in 2012, known as sustainable development goals (SDGs), guiding nations toward achieving a sustainable and greener future. Every participating nation and industry worldwide bear the responsibility of making changes within their capacities to contribute to UN SDGs. The ICT and Data Center industries are no exception. The environmental impact, whether positive or negative, is assessed using various indices termed as "Key Point Indicators (KPIs)" and is further detailed in the following section, encompassing both direct and indirect environmental impacts.

IV. Environmental Impact of Data Centers

The environmental sustainability of these facilities has come under scrutiny in recent years. Given the substantial amounts of environmental resources they consume and their significant contribution to global energy consumption, it is imperative to address the sustainability challenges associated with Data Centers. A green Data Center is termed as 'a Data Center system in which the mechanical, lighting, electrical, and IT equipment are designed for maximum energy efficiency and minimum environmental impact' (Reddy et al., 2017). In the absence of a detailed matrix for the analysis of the sustainability of Data Centers, the indicators of environmental impact and indices like (a) Power Usage Effectiveness (PUE), (b) Partial Power Energy Effectiveness (pPUE), (c) Data Center Infrastructure Efficiency (DCiE), (d) Carbon Usage Effectiveness (CUE), (e) Water Usage Effectiveness (WUE), (f) Electronics Disposal Effectiveness (EDE), (g) Energy Usage Effectiveness (EUE) are considered for comparisons after being proposed by the Green Grid Consortium. The overall picture of the Data Center's environmental impact is represented by the global carbon footprints resulting due to their overall functionalities. From 2010 to 2020, Data Center's global carbon footprints have increased at a rate of almost 300% (from 159 MT CO_2e to 495 MT CO_2e per year). (Figure 5.)

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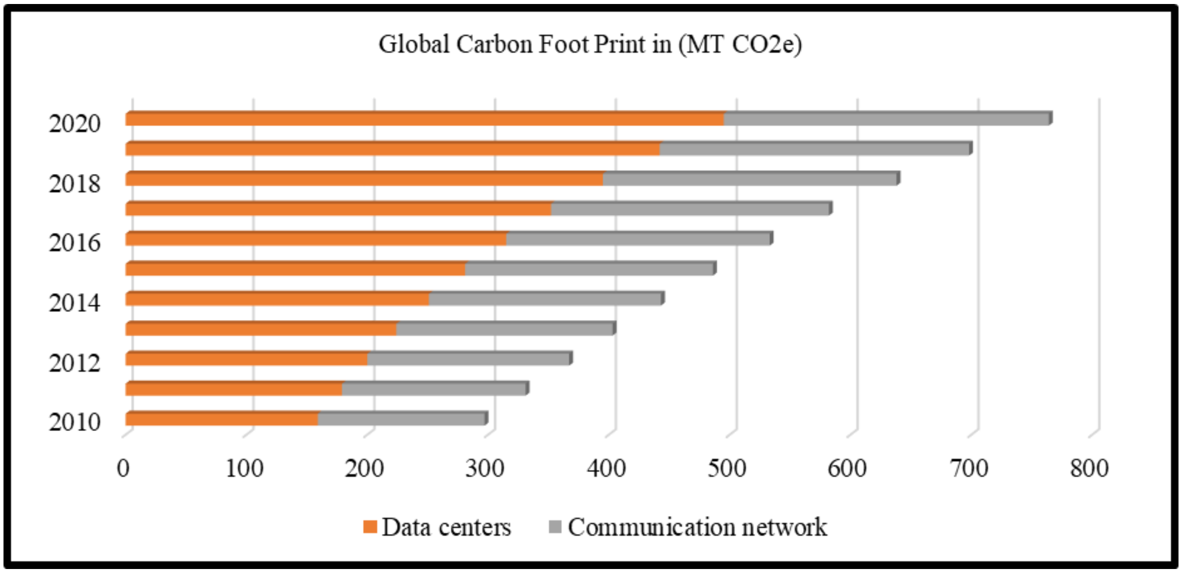

Figure 5: Global carbon Footprint (Mt CO_2e) – Data Centers (Al Kez D, et. al., 2022)

However, the world of Data Centers and their environmental impact-related information is fragmented, and researchers tend to find it inadequate at times. It is also observed that there are reports by Cooke et al. (2021) reporting carbon footprints significantly lower than the reports by Al Kez D, et al. (2022). In a nutshell, it is reported that the global carbon footprint of Internet use ranges from 28 to 63 g CO_2 equivalent per Gigabyte (GB). The water and land footprints are reported between 0.1–35 L/GB and 0.7-20 cm2/GB, respectively (Obringer et al., 2021). Technological advancements in the ICT field have helped technologists to reduce water footprints drastically with improved efficiencies in electronics, storage devices, and Data Center functionalities, but there is still a long way to go to make them completely sustainable.

To understand the environmental impact generated by DCs, we tried to compare the major categories of natural resources consumed by the Data Center and carbon footprints. The following sections discuss land, water, and energy consumption and their impact on the environment in the form of carbon dioxide emissions or the degradation of resources at large. Land/soil provides the space for the foundation of Data Centers on Earth. However, the scarcity of land for food production and fuel generation competes with the requirement for fertile land on the globe. The following table describes the area of the 10 largest data centers in the world (Table 1) (https://www.rankred.com/largest-data-centers-in-the-world/).

Data center	Area (sq. m)	City	Country
China Telecom Data Center	10763910	Hohhot	China
China Mobile	7750015	Hohhot	China
The Citadel Campus	7750015	Nevada	United States
CWL1 Data Center	1450000	Newport	Wales
Apple's Mesa Data Center	1300000	Arizona	United States
Lakeside Technology Center	1100000	Chicago	United States
Utah Data Center	1000000	Utah	United States
QTS: Atlanta Metro	990000	Atlanta	United States
Tulip Data Center	970000	Bengaluru	India
Core Site Reston VA3	940000	Northern Virginia	United States

Table 1: Ten largest Data Center in the world, their location and area (sq.m.)

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Research conducted by Al Kez D, et al. (2022) comprises a summary of Data Center land, water, and carbon footprint generated in the USA as depicted in the table below (Table 2: Energy sources, carbon, water, and land footprint generated by Data Centers in the USA).

Source	Carbon foortprint (g of CO2eq/kWh)	Water foortprint of elec-total (m^3/GJ)	Carbon foortprint (g of CO2eq/GB)-Data centers	Water foortprint (lit/GB)-Data centers	Land foortprint (cm^2/GB)-Data centers
Coal	910	3.654	1.685	0.024	0.278
Oil	866	2.744	0.028	0.000	0.000
Natural Gas	650	2.794	1.203	0.019	0.019
Nuclear	110	3.004	0.099	0.010	0.009
Hydro	2200	851.554	0.714	0.996	0.055
Bioenergy(biomass=wood+waste+geothermal)	420	65.554	0.035	0.020	0.672
Wind: Onshore	56	1.5552	0.021	0.002	0.005
Wind: Offshore	35	1.5552	0.000	0.000	0.000
Solar PV	180	1.857	0.027	0.001	0.023
Geothermal	79	2.313	0.000	0.000	0.000

Table 2: Energy sources, carbon, water, and land footprint generated by Data Centers (USA).

The analysis of the table indicates a huge potential for utilizing renewable energy sources for the functionalities of Data Centers in the USA. As these renewable sources tend to generate the lowest possible carbon, water, and land footprints, it is important to initiate processes to facilitate the transition of Data Centers to renewables in the coming decade.

Lawrence Berkeley National Laboratory, USA, in collaboration with Stanford University, has been working for a long time and has been recording and reporting Data Center-related data to the government (Koomey, J. G. et al., 2007; 2008). According to recent studies, data centers in the USA consume around 90 billion kilowatt-hours (kWh) of electricity annually, accounting for approximately 1.8% of the total electricity consumption in the country. It is projected that the energy consumption of data centers in the USA will reach approximately 73 billion kWh by the year 2020 (Moura et al., 2019).

Data Center energy consumption globally rose significantly from 205 terawatts (TW) in 2018 to 416 TW in 2020. Based on projections, global data centers might consume between 658 TW and 752 TW per hour by 2030 (Figure 6). This suggests a considerable environmental impact in terms of energy use and potentially related carbon emissions.

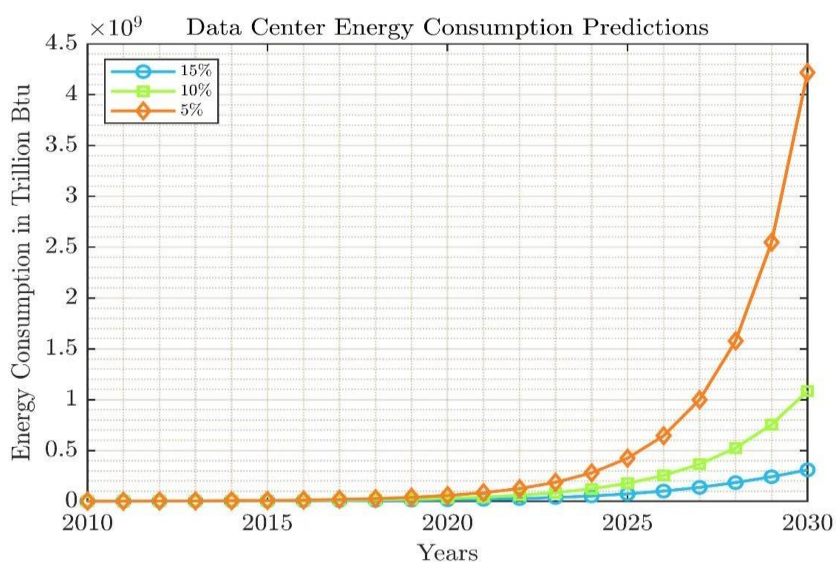

Figure 6: Data Center energy Consumption predictions (USA). Andrae and Edler, (2015).

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The research by Andrae and Edler (2015) represents energy consumption data in TWh/EB based on internet usage and traffic, as compared to current research where the focus is on energy consumption. Thus, the original data is multiplied by exabyte to get TWh and has been converted to trillion Btu to normalize units for comparison.

As reported by Hintemann and Hinterholzer (2020), 'Malmodin/Lunden calculate worldwide energy consumption of Data Centers to be 240 billion kWh in 2015; according to Van Heddegdem et al., no less than 270 billion kWh were needed in 2012. Bitterlin assumes that Data Centers worldwide required 416 billion kWh of energy in 2015.' Data centers are double-edged swords, as they help the world to travel less by providing internet-based platforms while being huge energy consumers and carbon emitters themselves. To make the Data Center's ecosystem more sustainable, it is inevitable to prepare sustainability matrices, environmental impact indicators, and nurture the process towards a greener future. The key indicators and possible energy transitions towards sustainable Data Centers are described in Table 3 below. The most inclusive list of indicators is presented in alphabetical order and adopted from https://www.sunbirddcim.com/infographic/top-30-data-center-sustainability-metrics.

Sr. No	Metric	Calculation	Unit
1	Air Economizer Utilization Factor (AEUF)	Time Air Economizer in Use / Total Time	Percentage
2	Airflow Efficiency	Fan Power / Airflow	W / cfm
3	Cabinets Compliant with ASHRAE Standards	Racks in ASHRAE Recommended Range / Total Racks	Percentage
4	Carbon Usage Effectiveness (CUE)	CO_2 Emissions / IT Energy	kg CO_2 / kWh
5	CO_2 Savings	Possible CO_2 Emissions / Actual CO_2 Emissions	Ratio
6	Cooling Capacity Factor (CCF)	Cooling Capacity / Critical Load	Ratio
7	Data Center Infrastructure Efficiency (DCiE)	IT Energy / Facility Energy	Percentage
8	Data Center Performance Efficiency (DCPE)	Useful Work / Facility Energy	Work / kWh
9	Data Center Performance Per Energy (DPPE)	Work / (Total Energy - Green Energy)	Ratio
10	Data Center Power Density (DCPD)	Rack Power Consumption / Rack	kW / Rack
11	Data Center Space Efficiency (DCSE)	RU Space Utilization x Floor Space Utilization	Percentage

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12	Delta-T Per Cabinet	Exhaust Temperature - Intake Temperature	°C or °F
13	Deployed Hardware Utilization Efficiency (DH-UE)	Minimum Systems to Handle Peak Load / Total Systems	Percentage
14	Deployed Hardware Utilization Ratio (DH-UR)	Servers Running Live Applications / Total Servers	Percentage
15	Energy Reuse Effectiveness (ERE)	(Total Energy - Reused Energy) / IT Energy	Ratio
16	Energy Reuse Factor (ERF)	Reused Energy / Total Energy	Percentage
17	Fixed to Variable Energy Ratio (FVER)	Fixed Energy / Variable Energy	Ratio
18	Green Energy Coefficient (GEC)	Green Energy / Total Energy	Percentage
19	Grid Utilization Factor (GUF)	Time Locally Generated Energy Covers Energy Demand / Total Time	Percentage
20	HVAC System Effectiveness (HSE)	IT Energy / HVAC Energy	Ratio
21	IT Equipment Energy Efficiency (ITEE)	IT Capacity / IT Energy	Ratio
22	Power Usage Effectiveness (PUE)	Facility Energy / IT Energy	Ratio
23	Space, Wattage, and Performance (SWaP)	Performance / (Space x Watts)	Ratio
24	Stranded Power Capacity Per Rack	Budgeted Rack Power - Actual Rack Power	kW / Rack
25	Technology Carbon Efficiency (TCE)	CO_2 Emissions / Facility Energy	bs CO_2 / kWh

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26	Temperature Per Cabinet	-	°C or °F
27	UPS Energy Efficiency (UPEE)	Input Powering the Load and Connected Systems / Total Input Power	Percentage
28	UPS Power Factor (UPF)	Actual Energy Consumed / Apparent Power	Ratio
29	Water Economizer Utilization Factor (WEUF)	Time Water Economizer in Use / Total Time	Percentage
30	Water Usage Effectiveness (WUE)	Water Usage / IT Energy	Ratio

Table 3: Key indicators for Data Center sustainability. *

*Adopted from https://www.sunbirddcim.com/infographic/top-30-data-center-sustainability-metrics

It is important to acknowledge the debate on the metrics and indicators for Data Center sustainability. Various energy-related authorities, accreditation agencies, vendors, researchers, and government policymakers have been struggling to adapt existing market indexes to Data Center functionalities. However, the need to create unique metrics and an inclusive approach has not been fulfilled yet. The opportunity lies in innovating the inclusion of renewable energy sources and materials usage to improve the index and bring transparency to the Data Center's sustainability black hole.

Out of the 30 indicators summarized in Table 3, more than 20 are directly or indirectly related to energy, grid efficiency, or related measurements, indicating a need for energy-related solutions for future Data Center architectures. Solar, Wind, Geothermal, Hydro, and biomass-based renewable sources can be a good alternative to lower fossil fuel-based consumption and reduce the carbon footprint. It is important to observe that increasing interest in renewable energy is driven by two major factors: (i) lowering environmental impacts (indirect saving, company reputation, trustworthiness, futuristic technology leadership, long-term gains, policy advantages) and (ii) direct savings on energy consumption. With estimated 2.3×10^6 servers corresponding to 9.3×10^6 MWh of electricity consumption. The question remains is it possible to rely on renewable energy sources for running data centers in USA?

V. Renewable energy sector in US: production and consumption trends

To answer that question, it is important to understand overall production and consumption trends of renewable energy in the USA. Figure 6 indicates the total renewable energy production and consumption trends, as well as the consumption trends of different sources of renewable energy over the past few years.

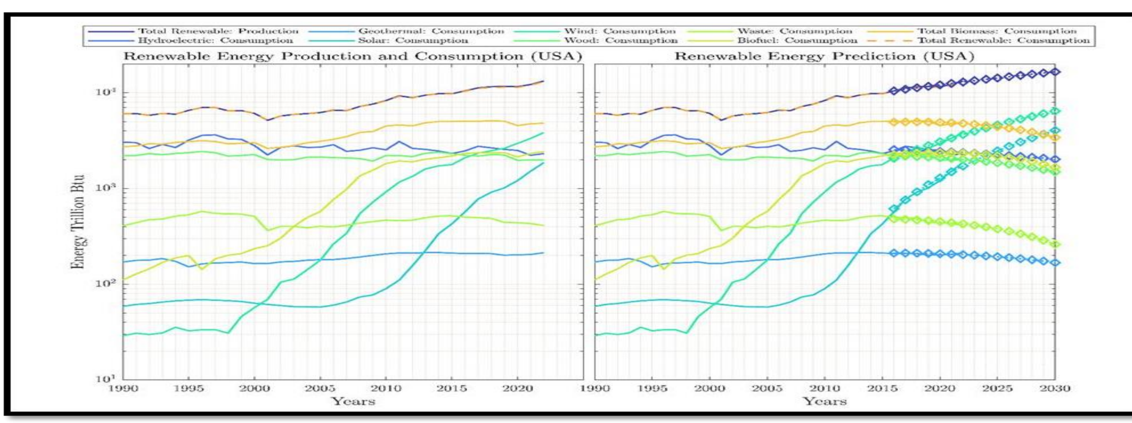

Figure 7: Renewable energy production, consumption, and future prediction trend in USA

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As observed in the graph above, there is an uphill trend in terms of production and usage of renewable energy in the USA. The prediction for the coming years has been estimated using the following quadratic equation:

$y=Ax^2+Bx+C$,

where x is the number of years, and y is the corresponding energy value. The coefficients A, B, and C were determined from consideration of the last 20 years of data, providing insight into the underlying trends.

It is evident from the prediction trends that the Wind and Solar based renewable energy consumption trends are likely to grow logarithmically in coming decades. The total renewable energy production and consumption trends go hand in hand indicating there is no shear lag in consumption, meaning the infrastructure has been effectively using all the generated renewable energy power over the time. In case of geothermal, hydroelectric and biofuel related energy generation, the field may become a little stagnant in terms of consumption. To evaluate the possibility of fuelling Data Centers with renewable energy, the predictions were compared using same energy units (Figure 7).

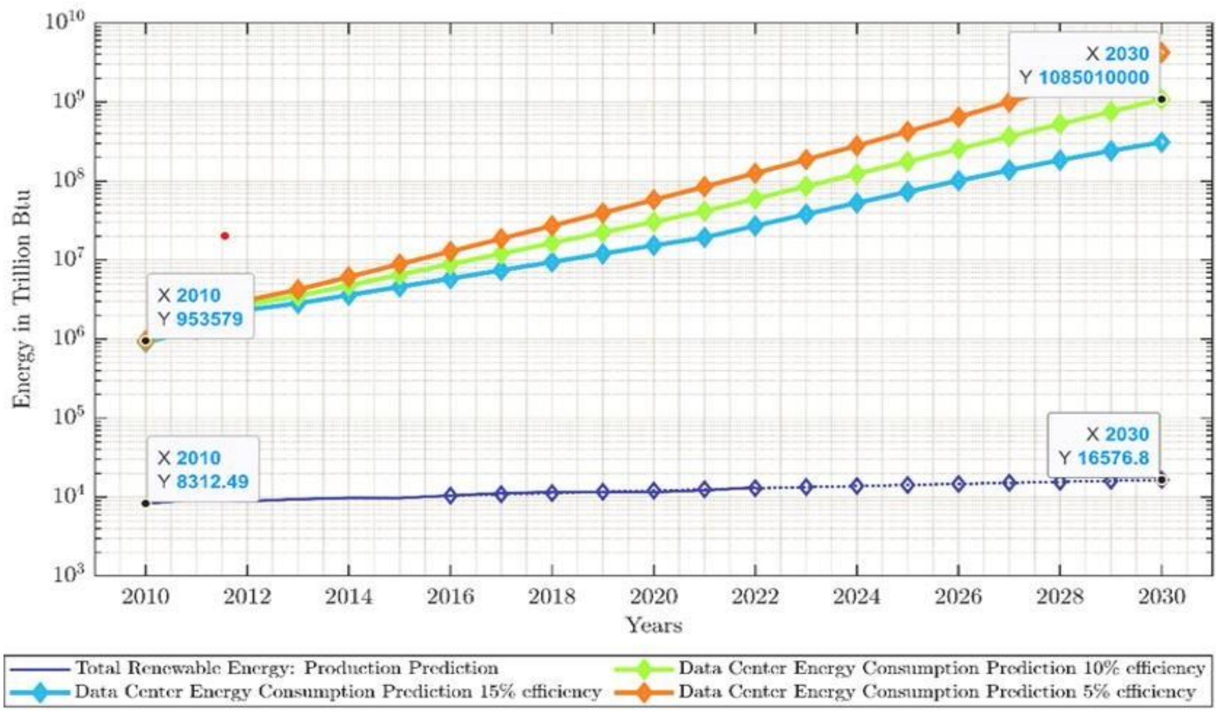

Figure 8: Comparison of Predictions

Aligning with the results by Andrae and Edler (2015), the analysis indicates a huge gap (of 105 folds) between renewable energy generation and Data Center's energy requirements. This indicates a substantial investment in creating infrastructure to generate and store renewable energy in the USA. It is also important to consider the overall production cost of energy generation. The projected cost of energy in 2021 is estimated to range from 1.98 US dollars per million British thermal units (Btu) for coal, up to 10.08 US dollars per million Btu for petroleum, with an average rate of 3.82 US dollars (https://www.statista.com/statistics/183992/average-costs-of-fossil-fuels-for-us-electricity-generation-from-2005/).

In 2015, the cost of wind power was estimated to be $0.025 per kilowatt-hour. Solar electricity is slightly more expensive; residential rooftop systems were estimated at an average of $0.12 per kilowatt-hour, with utility-scale solar electric farms costing around $0.05 (US Energy Information Administration and Lawrence Berkeley National Lab, respectively). This represented a 70 percent decrease since 2009 in the expenditure on solar energy production compared to other non-renewable sources, such as coal or natural gas, which typically generate costs of approximately $0.04 per kilowatt-hour (https://www3.uwsp.edu/cnr-ap/KEEP/nres635/Pages/Unit2/Section-B-Comparing-Renewable-and-Non-Renewable-Energy-Costs.aspx).

All the changes needed to transition them off-grid should be thoroughly evaluated for individual Data Centers based on their structures. Energy, being the major player in carbon footprint generation, offers two routes for any ICT company owning a Data Center to reduce their footprints. Either they can transform the Data Center facilities to fit nearby renewable energy sources (take

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the Data Center off the grid and fit it to a green energy source) or they can buy renewable energy. In recent reports, Apple committed to supplying 200 MW of solar power to their data center in Reno, Nevada. Similarly, Google has recently built a 300 MW solar farm to support its Data Centers

Implementation challenges for renewables in Data Centers

With the growth of renewable energy consumption, it seems very promising to opt for a transition in power supply for a Data Center and reduce their environmental impact significantly. However, each type of renewable source faces common and individual limitations in providing a reliable 100% power supply to the institution. Weather uncertainties and the intermittent and uncertain character of Renewable Energy production are found to be the most observed reasons in the survey-based research carried out by Rostiroll et al. (2021).

Type of renewable	Energy generated	Data Center perspective	Need for energy storage	Use
Wind	kW to MW	Real estate needs and costs, Location-dependent, Weather uncertainties	Yes	Amazon with 91 MW planned in Sweden, Apple with 200 MW in Oregon
Photovoltaics/Solar	kW to MW	High cost of photovoltaic solar arrays, Intermittency and density, day/night cycles	Yes	413 MW for Google in Alabama and Tennessee
Hydropower	kW to GW	Location-dependent	Yes	Microsoft, for its part, has built in Quincy, Washington, using 100 percent hydropower. A Data Center in the Swiss Alps claims to run with 99.9% hydropower
Biomass	--	Availability of the biomass resource	Yes	HP Labs designed a system capable of powering a 1 MW power Data Center using manure from 10,000 cows from a farm in Georgia, and in Ohio, they were abandoned.

Table 4: Comparison of Limitations of Renewable Energy Sources for Data Centers

Despite all the mentioned limitations, there is growing interest in the market to use renewables and transition for a better future. Apart from shifting to renewable sources, the US Department of Energy has created a master list of energy efficiency actions, divided into eight sections needing audits for better energy management.

- Global (GL)
- Energy Monitoring and Controls (EM)
- IT Equipment (IT)
- Environmental Conditions (EC)

- Cooling Air and Air Management (AM)
- Cooling Plant (CP)
- IT Power Distribution Chain (ED)
- Lighting (LT)

In addition to traditional energy-saving mechanisms, waste heat recovery is also an option that companies are trying to recirculate energy and reduce costs and emissions (Montagud-Montalvá, 2023).

Employing Predictive Modelling using Machine Learning to assess the long-term sustainability of Data Centers.

Employing predictive modelling using machine learning to assess the long-term sustainability of Data Centers is a crucial step in ensuring their efficient and environmentally responsible operation (Hoosain et al., 2022). Predictive modelling can provide valuable insights into the future performance and impact of Data Centers, allowing stakeholders to make informed decisions and implement effective strategies for sustainability (Kez et al., 2022). Several companies have employed machine learning for predictive modelling of Data Centers. For example, Google and Microsoft are two prominent companies that have embraced predictive modelling using machine learning in their Data Center operations. (Lim, 2022). These companies utilize machine learning algorithms to analyse large amounts of data and predict future trends in resource usage, energy consumption, and system performance. Predictive modelling can be used to identify potential problems before they become critical, allowing for proactive maintenance and repairs that reduce downtime and improve reliability of the facility. Additionally, predictive models enable Data Centers to better anticipate future resource needs to plan ahead accordingly. This type of analysis also helps organizations make informed decisions about their infrastructure investments by providing insights into how various changes may affect overall performance over time. Google has utilized DeepMind to great effect, leading to energy savings of approximately 30% and decreased costs associated with this. With Maya HTT's Data-center Clarity LC software, AI-powered tools are used for examining servers individually in order to identify anomalies as well as possibilities for optimization (https://www.techtarget.com/searchdatacenter/tip/How-machine-learning-in-data-centers-optimizes-operations). Researchers have also developed AI/ML based models for predictions of energy consumption trends. As an extrapolation of small machine learning programs, these predictive models can be fed with temperature, humidity, electricity consumption, server operations and usage related data and then can be used to maximize the efficiencies to be used in Data Centers (Koot and Wijnhoven, 2021). DCIM (**Data Center Infrastructure Management**) like analysis tools have been developed as a product for Data Center sustainability management and reporting. Under the government policies of reporting for the department of energy, tools like, On the other hand it is very important to know that these programs themselves use considerable amount of energy (https://aws.amazon.com/blogs/architecture/optimize-ai-ml-workloads-for-sustainability-part-1-identify-business-goals-validate-ml-use-and-process-data/).

Employing predictive modelling using machine learning to assess the long-term sustainability of data centers is a crucial step in ensuring their efficient and environmentally responsible operation (Hoosain et al., 2022). Predictive modelling can provide valuable insights into the future performance and impact of data centers, allowing stakeholders to make informed decisions and implement effective strategies for sustainability (Kez et al., 2022). Several companies have employed machine learning for predictive modelling of data centers. For example, Google and Microsoft are two prominent companies that have embraced predictive modelling using machine learning in their data center operations (Lim, 2022). These companies utilize machine learning algorithms to analyse large amounts of data and predict future trends in resource usage, energy consumption, and system performance. Predictive modelling can be used to identify potential problems before they become critical, allowing for proactive maintenance and repairs that reduce downtime and improve reliability of the facility. Additionally, predictive models enable data centers to better anticipate future resource needs to plan ahead accordingly. This type of analysis also helps organizations make informed decisions about their infrastructure investments by providing insights into how various changes may affect overall performance over time. Google has utilized DeepMind to great effect, leading to energy savings of approximately 30% and decreased costs associated with this. With Maya HTT's Data-center Clarity LC software, AI-powered tools are used for examining servers individually in order to identify anomalies as well as possibilities for optimization (https://www.techtarget.com/searchdatacenter/tip/How-machine-learning-in-data-centers-optimizes-operations).

Data Center operators have also developed AI/ML-based models for predicting energy consumption trends. As an extension of existing machine learning algorithms, these predictive models can be fed with temperature, humidity, electricity consumption, server operations, and usage-related data and then can be used to optimize Data Center operations (Koot and Wijnhoven, 2021). DCIM (Data Center Infrastructure Management) like analysis tools have been developed as a product for Data Center sustainability management and reporting. While it is important to consider the energy consumption of AI/ML programs

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themselves, as they can require significant amounts of power to operate, the overall energy savings achieved through the use of AI/ML in data center optimization can outweigh the energy consumption of the programs themselves. (https://aws.amazon.com/blogs/architecture/optimize-ai-ml-workloads-for-sustainability-part-1-identify-business-goals-validate-ml-use-and-process-data/).

V. Case study

Meta is a leader in data center sustainability, having made significant progress in recent years. This case study will explore their impressive achievements and demonstrate how they are helping to minimize their environmental footprint through responsible resource use. In terms of water consumption, Meta has been able to reduce their total water usage from 45 million gallons per year down to 24 million just within 5 years' time. These reductions have also translated into significant financial savings for the company, resulting in an estimated $4 million dollars saved each year. In addition, Meta also boasts impressive reductions when it comes to electricity use, achieving 26% lower levels of electricity consumption than before with 27 megawatts consumed yearly compared against 37 previously used annually. These reduced energy expenses led them to save another substantial sum totalling $7 million on average every single year. Most significantly, these combined initiatives resulted in a staggering 638 metric tons of carbon dioxide emissions being avoided or prevented annually.

Meta's data center located in the USA directly benefits the local environment by reducing carbon dioxide emissions throughout America. Its efforts alone have contributed to preventing the release of thousands of tons of greenhouse gases into our atmosphere each year, equivalent to taking almost 137 cars off the road. By moving away from more traditional power sources like coal or gasoline-burning vehicles, these risks are significantly mitigated, all while helping to reduce air pollutant levels across multiple states. https://sustainability.fb.com/2023-sustainability-report/.

VI. Conclusion

The ascending trends of renewable energy production indicate an encouraging prospect of shifting Data Centers off the grid shortly. Conversely, transitioning from conventional power sources necessitates substantial scaling up of renewable energy generation for potential candidates such as wind and solar power. In conclusion, addressing the environmental impact of Data Centers requires a holistic approach that considers both embodied and operational emissions (Hoosain et al., 2022). To design a strong strategy towards a greener future for Data Centers, it is important to pursue two methodologies simultaneously: (a) Execution of rigorous standards, recycling norms for sustainability, and transparent reporting to reduce existing waste and energy-related footprints. (b) Investing in research related to technological advancements for reducing transitioning costs for Data Centers. This collaborative effort between stakeholders in the Data Center industry, policymakers, and environmental organizations aims to foster discussions and collaboration for the development of greener Data Centers in the future.

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