Towards Sustainable Cloud Computing: A Comparative Evaluation of Carbon Footprint Calculator Tools

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Abstract: As modern businesses grow; cloud computing has become an indispensable tool thanks to its scalability and convenience. However, it is essential to recognize the severe impact it has on the environment. Our study delves into the various carbon footprint calculator tools provided by major players in the cloud industry. By comparing and contrasting these tools, we shed light on their limitations and strengths, including crucial aspects like data precision and geographical variations. These tools, however, provide valuable information but fail to include critical features like real-time tracking of carbon emissions and personalized alerts to indicate threshold crossings. We also stress the need to monitor other aspects, including often neglected water utilization and the carbon footprint of these tools themselves. Our analysis suggests combining machine learning to optimize carbon offsetting measures and calculate carbon footprints dynamically. Furthermore, cloud providers could integrate real-time monitoring and custom alerts to enhance the user experience. This study not only analyses the tracking of carbon emissions but also encourages users to actively address their environmental impact. This critical area of sustainability demands that organizations assess and reduce their carbon footprint in the Cloud. This can be achieved by adopting eco-conscious cloud computing practices. This paper offers a comprehensive guide on the subject, including a roadmap for further research. Its conclusion affirms the importance of addressing cloud computing's environmental impact.

1 INTRODUCTION

Contemporary technology infrastructure is built on cloud computing in today's digital age [1]. Amidst the digital world's constantly shifting landscape, the scalability, efficiency, and adaptability of cloud computing drive business innovation and process optimization. However, the often-neglected environmental impact of cloud services warrants deeper consideration, especially with the world's growing dependence on cloud solutions [2]. Aiming to minimize their environmental impact and increase their sustainability efforts, organizations globally are prioritizing the reduction of their carbon footprint in the face of mounting imperatives to combat climate change [3]. The environmental impact of cloud computing compared to traditional on-premises computing solutions is significant. For instance, Microsoft's cloud is 93% more energy-efficient and 98% more carbon-efficient than on-premises data centers. Similarly, Google managed a 550% increase in cloud data centers from 2010 to 2018, with only a 6% increase in energy consumption.

The IT sector's energy consumption and carbon emissions, encompassing cloud services and data centers, have been intensely scrutinized [4][5]. As such, cloud providers have commendably optimized their operations to address these concerns. A crucial question arises amidst these efforts to promote sustainability. How can organizations accurately measure and reduce the carbon emissions associated with cloud usage? This is where carbon footprint calculator tools come into play.

These tools, available from major cloud providers, are designed to provide data-driven insights into the carbon footprint of cloud services. By offering this information, they empower eco-conscious decision-making and support efforts to reduce carbon footprint. The realm of carbon footprint calculators is far from standardized. Every

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significant cloud provider has their rendition of these instruments. They diverge in their accessibility to data, frequency of updates, precision of values, regional categorization, and how they display summaries of emissions and savings. Although these tools provide helpful observations, they each have advantages and drawbacks. Our research paper takes a thorough expedition into the realm of cloud carbon footprint calculators. The approach involves meticulously examining the tools provided by various cloud service providers. Customer Carbon Footprint Tool offered by Amazon Web Services (AWS), Microsoft Sustainability Calculator provided by Azure Cloud, Carbon Footprint from Google Cloud Platform (GCP) and IBM Cloud's IBM Cloud Carbon Calculator are analyzed extensively in this work. The name of the cloud service provider and the name of the tool offered by it are used interchangeably throughout the text, unless stated otherwise.

Through this process, we conduct a comprehensive comparison to uncover the subtleties that differentiate each one. The goal is to equip individuals and organizations with a thorough understanding of these tools to make informed decisions and take steps towards reducing their carbon footprint when utilizing and providing cloud services. Our exploration continues even after this point, and as we further examine the inner workings of these calculators, we discover significant deficiencies in their capabilities. We bring attention to the absence of a facility for real-time monitoring of carbon emissions, the incapacity of users to establish personalized threshold alerts and other ecological factors that are usually sidelined. Moreover, our vision for the future involves the progression of these tools to provide users with the data and practical methods to counteract their negative impact on the environment [6]. We propose integrating machine learning for dynamic carbon footprint calculations and optimizing carbon offsetting measures. The vision is to measure emissions and actively engage users in mitigating their environmental impact.

The study presented in this paper emphasizes that the only way to reduce the environmental impact of this growing cloud services industry is to do it passively by reducing energy consumption and emissions. Unlike other sectors like manufacturing, active carbon capture at the source is not feasible. The remaining paper is organized as follows. Section II is structured into four parts. Part A details the four cloud providers' carbon footprint calculation tools. Part B outlines the sources of data used for comparing these tools. Part C introduces the comparison framework that guided the evaluation process. Part D elaborates on the broader methodology employed for calculating carbon emissions. Section III presents results and analysis based on a comprehensive evaluation of various factors. Section IV outlines potential future work to enhance the efficiency and accuracy of the tools for better practical implementation and broader impact. Finally, Section V concludes the paper.

2 STUDY

The methodology employed in this research paper is designed to comprehensively compare and evaluate the carbon footprint calculator tools offered by various cloud providers. This study aims to assess these tools' capabilities and limitations, shed light on their functionalities, and offer insights into how they contribute to sustainable cloud computing practices. It also aims to help customers choose eco-friendly cloud services that align with sustainability goals and save money [7]. Furthermore, it improves the understanding of the environmental impact of cloud computing and encourages providers to reduce their carbon footprint. This leads to more robust and reliable carbon measurement tools.

2.1 Overview of the carbon calculator tools

1. **Customer Carbon Footprint Tool by AWS-** The AWS Customer Carbon Footprint Tool allows users to examine the estimated carbon footprint associated with using AWS services, facilitating the accurate assessment of an organization's overall carbon footprint and monitoring emissions reductions over time. The tool utilizes the Greenhouse Gas Protocol to calculate estimates, presenting the information through easily comprehensible data visualizations. Access to the Customer Carbon Footprint Tool is available through the billing dashboard, requiring a new AWS identity and access management permission.
2. Users are offered various options to customize their analysis by setting preferred periods. The estimates are delivered monthly, allowing users to review data as far back as January 2020 retrospectively. As users configure their desired time frames, the dashboard dynamically updates to display the estimated carbon emissions generated during the selected periods. Users will find five distinct sections within the tool offering insights into their carbon emissions from AWS services. The first section

presents estimated AWS emissions, depicted in green, representing the combined scope one and scope two carbon footprint for the selected time, measured in metric tons of carbon dioxide equivalent.

3. To offer context, the tool utilizes data sourced from 451 Research, an advisory organization that is part of S&P Global Market Intelligence, to calculate the carbon emissions saved by operating workloads on AWS rather than on premises. Users can gain visibility into the geographic distribution of their emissions, derived from the specific services used in each AWS region and aggregated by geography.

4. Furthermore, the tool furnishes a breakdown of emissions by broad AWS service based on users' historical usage. Users have the flexibility to review emission changes over time, with data available monthly, quarterly, or yearly. Additionally, the tool offers a forecast of future carbon emissions based on current AWS usage patterns and AWS' renewable energy project roadmap. This projection illustrates how carbon emissions will evolve over the coming years. Users can observe changes in their forecast as their usage patterns shift, and AWS introduces new renewable projects globally. This dynamic feature allows users to track and anticipate alterations in their carbon footprint over time. Fig. 1(a) illustrates the dashboard of Customer Carbon Footprint Tool By AWS.

IBM Cloud Carbon Calculator- The Cloud Carbon Calculator Dashboard offers clients access to emissions data for various IBM Cloud workloads, including High 1 Performance Computing (HPC) and financial services. This tool presents a range of features for tracking carbon emissions, allowing users to view total emissions by service, resource group, and location. Additionally, it facilitates data analysis by enabling the filtering of emissions data based on time period, service, or location and supports data export in CSV format for further examination. The calculator helps explicitly estimate electricity consumption and associated greenhouse gas (GHG) emissions for select IBM Cloud services, thus providing insights on a per-account, per1service, per-location, and resource group basis. Fig. 2(b) shows the Carbon Calculator dashboard offered by IBM cloud.

Carbon Footprint by Google Cloud- In the Google Cloud environment, a dedicated carbon footprint dashboard is accessible through the console, providing visibility to individuals with billing admin rights. This dashboard features precise infographics, offering comprehensive insights into total emissions categorized by project, month, product, region, and more. The same functionality extends to Workspace customers, ensuring a consistent user experience. Users also have the option to export the data to BigQuery, facilitating custom analytics and visualizations. This exported data can be utilized to meet sustainability reporting requirements, particularly in the auditing of scope three greenhouse gases.

Carbon Footprint builds its calculations from bottom to top, relying heavily on machine-level power and activity monitoring inside Google data centres.

Google has introduced a key metric, the Carbon-Free Energy Percent (CFE), to empower users to select regions with higher CFE percentages. Regions with higher CFE percentages are preferable as they contribute to fewer carbon emissions. This information is integrated into many of Google Cloud's products, and when users choose a region, a user-friendly low CO2 icon is displayed in the Cloud Console. Additionally, this icon is annotated on the locations page of the documentation for various products, enhancing user awareness of the environmental impact associated with their choices. Fig. 3(c) pictorializes how Carbon Footprint by GCP provides emissions summary.

Microsoft Sustainability Calculator by Azure- The Emissions Impact Dashboard, powered by Microsoft Power BI and Microsoft Azure Data Explorer, allows employees to monitor the environmental impact of their Azure virtual machine usage. It encourages proactive measures, such as optimizing design systems or downsizing virtual machines based on real-time data. The

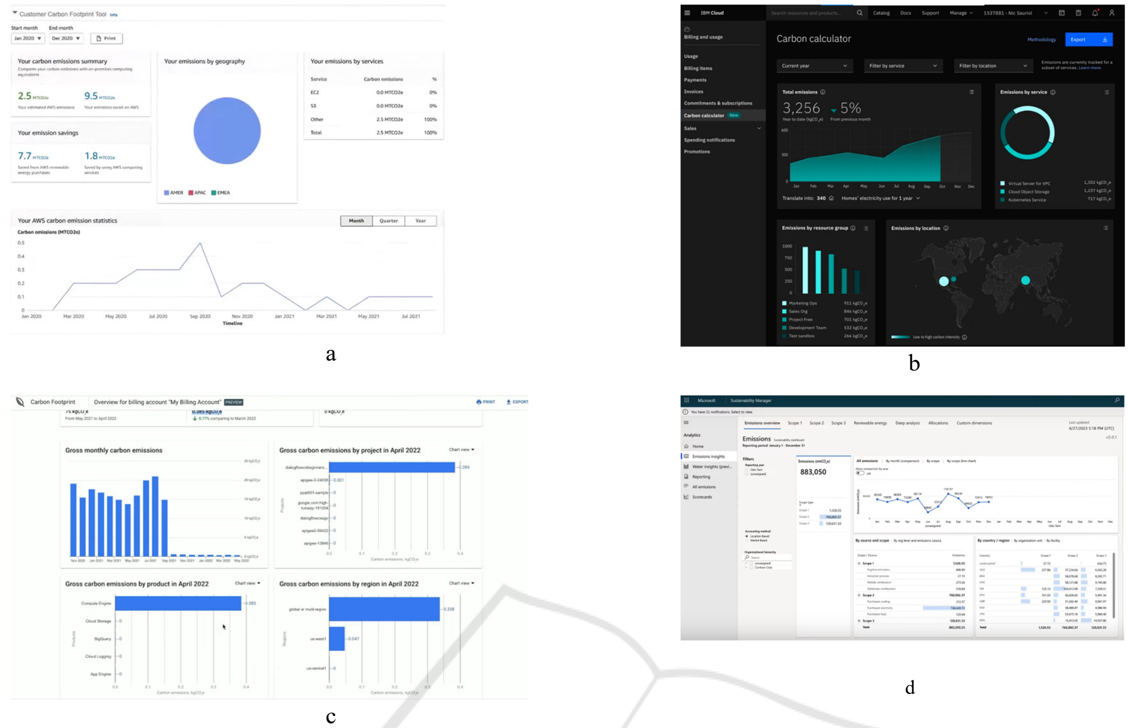

Fig. 1 (a) Customer Carbon Footprint Tool dashboard by AWS, (b) Carbon Calculator dashboard by IBM, (c) Overview dashboard of Carbon Calculator by GCP, (d) Emissions Insights on Microsoft Sustainability Calculator by Azure.

dashboard integrates seamlessly with the Sustainability Manager, offering a connector to import data for tracking carbon emissions across different scopes, including scope three emissions from Azure services. Access to this dashboard requires an Enterprise Agreement (EA) enrollment number, billing account ID, and admin access. It ensures transparency by utilizing billing information to allocate carbon emissions, respecting user privacy and permission settings. Specifically designed for Microsoft 365, the Power BI app provides a clear quantitative overview of greenhouse gas emissions associated with organizational use, including Teams calling, file storage, and SharePoint. Verified by a third party, the methodology covers all three scopes of emissions. The Emission Savings tab estimates the avoided greenhouse gas emissions achieved by using the Cloud over on-premises alternatives, emphasizing the up to 98 percent higher carbon efficiency of the Microsoft cloud. Users can customize estimates based on on-premises efficiency and the volume of renewable energy purchased by their organization. Fig. 4(d) depicts the Emissions Insights as displayed on Microsoft Sustainability Calculator.

2.2 Data Sources and Collection

The carbon footprint calculator tools and official documentation provided by the respective cloud providers are the main data sources for this research. Our sources include press releases and announcements from major providers like Google Cloud Platform, AWS, Microsoft Azure, and IBM Cloud. Collecting data involves obtaining and analyzing information about the functions, characteristics, and technical specifications of each calculator tool [8][9][10][11]. Not only that; also, apart from these we dig into any other probable unveiled dimensions surrounding these calculators to ensure a comprehensive review.

2.3 Comparison Framework

To facilitate a structured and meaningful comparison, we have established a comprehensive framework that considers a range of critical factors:

• **Cost**: Cost involved in using carbon calculator tools for emissions measurement and management.

• **Data Availability and Frequency**: Indicates the accessibility and update frequency of carbon emissions data within the tools.

• **Rounding of Emission Values**: Sheds light on the precision and accuracy of the emissions reporting.
• **Presentation of Emissions and Savings Summaries**: Describes how the tools display estimated carbon emissions and emissions savings, often compared to on-premises workloads.
• **Geographical Breakdown of Emissions**: Shows the carbon emissions data categorized by geographical regions, like continents or countries.
• **Breakdown by Specific Cloud Services**: Displays carbon emissions linked to specific cloud services. For example, EC2 vs S3 emissions in AWS cloud.
• **Emissions Trends Over Time**: Illustrates how historical carbon emissions data is presented over time (e.g., monthly, or yearly).
• **Path to Renewable Energy Adoption**: Graphically represents how carbon emissions decrease as the cloud provider transitions to renewable energy sources.
• **Adherence to Recognized Standards**: This ensures if the tools follow established norms, like the Greenhouse Gas Protocol and ISO standards, for reliable measurements. This involves Scope 1 emissions indicating direct emissions from an organization's activities, Scope 2 emissions cover indirect emissions from purchased electricity while Scope 3 emissions refer to indirect green-house gas emissions that occur from activities outside an organization's direct control.
• **Consideration of Regional Variations**: Considers regional differences in emissions based on the energy grid mix.
• **Differentiation Between Estimates and Actual Emissions**: Distinction between estimated and actual emissions for transparency.
• **Integration with Provider's Carbon Reporting Framework**: Refers to how well the carbon reporting framework integrates with the organization's sustainability reporting, enabling organizations track, evaluate, and report their carbon emissions and other sustainability factors.

2.4 Calculation of carbon emission

Calculating the carbon footprint of cloud services involves a step-by-step process [12]. First, the tools and service providers collect information about the services used along with their respective quantities. Next, they determine the energy usage as a function of cloud utilization and computation resource requirements. The next step is to obtain the total emissions by multiplying the electricity consumption by the corresponding carbon emissions per unit of electricity usage to calculate the total emissions. Here, the carbon emissions per unit of electricity usage vary with location and the carbon intensity of the source used to power the respective data centres [13].

These tools may normalize the result to ensure fairness, measuring emissions per service unit. The objective is to comprehend and compare the environmental impact of diverse online activities.

Although all the primary carbon emissions tools employ a similar methodology to estimate the carbon footprint, slight variations exist. AWS's Customer Carbon Footprint tool follows the Greenhouse Gas Protocol (GHG) to calculate its carbon footprint. IBM Cloud Carbon Calculator uses a non-automated, report-based process. It allocates a portion of the electricity consumption to each one of the services in a location based on the physical hosts being used.

It is essential to note that the accuracy of these calculations relies on the information provided by the companies delivering these online services. There is a lack of literature on the elaborate implementation of these services in the public domain.

3 RESULTS AND ANALYSIS

Table 1 comprehensively compares the key features of major cloud providers. AWS and GCP offer their carbon calculators free of charge, providing a low barrier to entry for users looking to assess their environmental impact. On the other hand, Azure requires a Power BI Pro license for installation and use. IBM Cloud's carbon calculator is complimentary with the billing service, which also costs similar.

GCP excels in data update frequency by providing daily updates, ensuring users can access the most current information. At the same time, Azure and IBM Cloud offer monthly updates. GCP also leads in data availability, allowing users to access the previous year's data. At the same time, AWS and IBM Cloud have data availability of 36 months, while Azure keeps data for the last 2 years.

AWS, Azure, and GCP round their emissions values, albeit to varying decimal places. In contrast, IBM Cloud rounds emissions values to the nearest whole number of metric tons of carbon equivalent (MtCO2e), potentially sacrificing granularity for simplicity.

AWS and Azure offer summaries of estimated emissions and potential savings relative to on-premises workloads. GCP excels in this area, providing a comprehensive overview of gross carbon emissions, carbon-free energy percentages, and average emissions intensity of the electricity grid.

IBM Cloud focuses on total emissions, resource groups, and location summaries. However, it does not offer information on potential savings, possibly missing an opportunity to showcase the environmental benefits of cloud migration.

Organizations with global operations need to factor in the distribution of emissions around the globe. AWS, Azure, and GCP provide insights into regional emissions. However, AWS groups regions by North, Central, and South America (AMER) and Europe, the Middle East, and Africa (EMEA), whereas GCP offers a more detailed breakdown. IBM Cloud offers a geographical breakdown but does not elaborate on the carbon emissions factor of each location.

AWS, Azure, and GCP offer emissions breakdowns by specific services, empowering users to pinpoint areas of concern. IBM Cloud follows suit but also provides information on the electricity consumption of each service, enhancing the tool’s utility.

AWS, Azure, and GCP offer visualizations illustrating the path to renewable energy adoption, aligning with their sustainability commitments. Although committed to similar goals, IBM Cloud does not provide forecasts related to renewable energy adoption. This could be an area for improvement to showcase IBM's commitment to sustainability. All companies adhere to the Greenhouse Gas Protocol and ISO requirements for greenhouse fuel reporting while contrasting the divide between estimates and actual emissions. Only AWS lags in considering scope three emissions among the four.

This comparison highlights limitations, emphasizing the need for more precise calculators. It also guides the strategy for developing a robust cloud carbon footprint calculator and how companies can adapt by integrating advantageous features from other providers if they lack tools. Moreover, this comparison proves invaluable for hybrid cloud usage, helping users identify which service emits fewer carbon emissions within each cloud provider, ultimately aiding in selecting the most eco-friendly and cost-effective cloud provider for specific workloads. This supports a multi-cloud approach to minimize carbon emissions.

Although these tools are primarily designed to mitigate and manage environmental impacts, particularly carbon emissions, they also offer cost benefits. Optimizing resource allocation by identifying inefficiencies can significantly cut operational expenses. Monitoring energy consumption enables businesses to adopt energy-saving measures, reducing electricity bills and overall costs. Additionally, prioritizing renewable energy adoption supports sustainability goals, stabilizes energy costs, and reduces expenses.

It's important to note that exact statistics regarding carbon emissions, energy efficiency, and other environmental impacts depend on various factors such as usage patterns, services employed, cloud provider, and usage intensity. These statistics are typically accessible to users through their respective cloud dashboards. While this paper provides thorough insights and analysis, the actual numerical values may vary based on specific usage scenarios and configurations.

4 FUTURE DIRECTIONS

The comparative analysis of carbon emission calculator tools has unearthed numerous crucial areas for future exploration and enhancement. These regions embody the following areas.

Real-time Carbon Emission Calculation: One observation is the absence of tools providing real-time carbon emission statistics. Such real-time information holds enormous value for numerous reasons: real-time emission monitoring and assessment, resource optimization, real-time alerts, and compliance.

Threshold Based Alerts: Currently, carbon emission tools cannot set personalized thresholds, triggering alerts if emissions cross the set limit. This feature, like cost tracking from providers like AWS, empowers customers to plan their usage and proactively be mindful of their emissions.

Self-Emission of Tools: It is imperative to understand that the tools' constant monitoring, calculations and relaying of carbon emissions data can add to the overall values, even in modest quantities. This cumulative impact must be recounted and addressed as a part of improvement and optimization.

Comprehensive Environmental Impact Reporting: Future updates of the tools should encompass dashboards and sections committed to displaying a broader spectrum of environmental impacts due to various cloud activities, like water utilization and emissions, during the establishment of the cloud infrastructure.

Carbon Offset Integration: Future advancements should include features that guide users in reducing their carbon footprint. This can be achieved by connecting the tool to carbon offset registries,

Table 1. Comparison of Carbon Calculator Tools by Various Cloud Providers.

Features	Customer Carbon Footprint Tool by AWS	Microsoft Sustainability Calculator by Azure	Carbon Footprint by Google Cloud	IBM Cloud Carbon Calculator by IBM
Cost and Accessibility	Free	Power BI Pro licence required to install the tool	Free	Free with billing service
Data Availability and Frequency	Three-month delayed update, data availability for past 36 months	Monthly updates, data availability for past 2 years	Daily updates, data availability for past 1 year	Monthly updates, data availability for past 36 months
Rounding of Emission Values	Rounded to the nearest two decimal places	Rounded to the nearest whole number	Rounded to the nearest two decimal places	Rounded to the nearest whole number
Presentation of Emissions and Savings Summaries	Relative to on-premises workloads	Relative to on-premises workloads	Overview of gross carbon emissions, carbon free energy percentages, and average emissions intensity of the electricity grid	Total emissions, resource group, and location summaries
Geographical Breakdown of Emissions	Yes, grouped by AMER and EMEA	Yes, detailed breakdown by source, scope, region etc	Yes	Yes, but does not elaborate on the carbon emissions factor of each location
Breakdown by Specific Cloud Services	Yes	Yes	Yes	Yes, also provides information on the electricity consumption of each service
Emissions Trends Over Time	Yes, monthly, quarterly, or annual views	Yes, monthly, quarterly, or annual views	Yes, monthly, quarterly, or annual views	Yes, monthly, quarterly, or annual views
Path to Renewable Energy Adoption	Yes	Yes	Yes	No
Adherence to Recognized Standards	Yes, Greenhouse Gas Protocol and ISO requirements; includes Scope 1 and 2 emissions	Yes, Greenhouse Gas Protocol and ISO requirements; includes Scope 1, 2, and 3 emissions	Yes, Greenhouse Gas Protocol and ISO requirements; includes Scope 1, 2 and 3 emissions	Yes, Greenhouse Gas Protocol and ISO requirements; includes Scope 1, 2 and 3 emissions
Consideration of Regional Variations in Emissions	Yes	Yes	Yes	Yes
Differentiation Between Estimates and Actual Emissions	Yes	Yes	Yes	Yes
Integration with Provider's Carbon Reporting Framework	Yes	Yes	Yes	Yes

allowing users to find and select projects that balance out their carbon emissions. Moreover, there could be a default choice suggesting tree planting, as a single tree can offset about one metric ton of carbon dioxide during its lifetime. Additionally, automated reminders can be sent to users at regular intervals, recommending carbon offsetting methods based on their usage patterns. This encourages active steps to reduce one's environmental impact.

Machine Learning for Real-time Calculation: More accurate machine learning models can be incorporated to bridge the gap between the estimates and actual emissions by leveraging cloud usage patterns and emissions data. Also, Machine learning offers carbon footprint reduction advice by suggesting practices like data deduplication, thin provisioning, tiered storage, energy-efficient hardware selection, optimal data centre locations, and efficient cooling systems [14]. The lack of available literature and implementation indicates this is relatively unexplored territory. We see significant potential in properly leveraging ML for enhanced accuracy and facilitating the implementation of offsetting measures [15]. For instance, understanding how much carbon can be generated based on usage and proposing corresponding measures represents an area where ML could make a valuable impact. Our proposal recognizes the necessity for exploration and advancement in this domain.

In essence the development of carbon emission calculation tools should prioritize measurements. Offer services that deliver actionable insights to support sustainability initiatives. Features like real time monitoring, threshold alerts, comprehensive environmental reporting and integration with carbon offsetting mechanisms can transform these tools into resources for organizations committed to reducing their carbon footprint while promoting sustainability.

5 CONCLUSION

The technological marvels of the today's era are built on reliant cloud services. Hence, it is important not to undermine the environmental impacts caused by the rapid expansion of cloud services. Few major players power most of the cloud services available today, and often in the pursuit of profits and expansion, the impact of this growth is neglected.

This paper delves into the carbon footprint calculator tools by these major players. The study examines the carbon monitoring tools by cloud service providers like Google Cloud, Amazon Web Services, Google Cloud Platform, and IBM Cloud and sets them apart by pointing out their subtleties and nuances. Though these tools offer insights into carbon emissions, they lack in real time tracking and the facility to enable personalized threshold alerts.

This study is a call for action to all the cloud service providers. Our study advocated for accountability by spreading user awareness regarding their usage and emissions while allowing for options to offset the carbon footprints. By ecological practices in cloud computing, we can strive towards a coexistence of technology and sustainability.

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