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PEMC: Power Efficiency Measurement Calculator to Compute Power Efficiency and CO_2 Emissions in Cloud Data Centers

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ABSTRACT The power consumption of cloud data centers has a considerable impact on the environment and climate change nowadays. Researchers are seeking to find practical solutions to reduce power consumption in data centers while guaranteeing the desired level of services and service level objectives. With the establishment of the data center industry, the demand for computation and data storage has been continually rising. Energy efficiency is one of the most significant issues faced by these big data centers to meet such high computational requirements. There are many industry acceptable metrics available such as PUE, DCiE, DCP, etc. Power Usage Effectiveness (PUE) metric has proven to be the most popular in measuring energy efficiency; however, it measures the power efficiency alone with no consideration for CO_2 emissions and the costs involved in total power usage across data centers. In this article, we proposed a novel Power Efficiency Measurement Calculator (PEMC) that combines and calculates the power efficiency, CO_2 emissions, and the total annual costs incurred. The pseudocode and algorithm to perform these specific PUE, DCiE, and CO_2 emission functions are given to explain the working of proposed work. Finally, the proposed PEMC calculator was tested and validated through a case study performed in one of the tier-level data centers in Malaysia and the results demonstrate its effectiveness compared with Power Usage Effectiveness (PUE) and other known calculators.

INDEX TERMS Cloud computing, data center, computer storage, network resources, power efficiency, CO_2 emission.

I. INTRODUCTION

The information and communication technology (ICT) sector has shown tremendous exponential growth in recent years. The continuous rise in the expansion of the Internet platforms and infrastructures, such as the Internet of Things (IoT), cloud computing paradigms and big data analytics, has led to the hotheaded evolution in the enormous increase in the production of computational data in almost every computing industry and business enterprise. The Internet of Things (IoT) is an evolving notion that connects billions of mobile devices and has attracted widespread attention from academia, industry, and governments around the world. These IoT devices sense, accumulate, and transmit massive amounts of essential and significant information from their surroundings. This exchange amongst billions of IoT mobile devices creates enormous energy and power consumption needs. An essential component of the ICT organizations is constituted by the data centers that are densely populated with redundant servers and communicational links to ensure the provision of 99.99% availability of services, a fact responsible for the substantial power consumption by data centers. Data centers have resolved all concerns regarding networking and storage. Now we can store gigabytes to terabytes of data on commodity servers [1] which are designed from off-the -shelf commodity parts for keeping it low cost and this data can be accessed from anywhere anytime. With the growth in mobile technology, billions of devices are participating in the IoT paradigm. The information they produce and the process need to be stored somewhere. This information can then be fetched

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using cloud platforms. Data centers act as a backbone for IoT (Internet of Things) and cloud applications.

The immense exponential increase in various data-driven amenities and services like audio-video streaming services, social networks, e-government and e-business applications, as well as e-commerce and m-commerce has driven rapid enlargement in the size and number of data centers and an increase in their power consumption. This leads to the increasing capacity and complexity of these large data center communication networks and their mounting footprints compared to the traditional public Internet infrastructures. Due to ever-increasing computational strain, the need for more extensive and large-tier level cloud data centers is getting enormous attention and becoming a pre-requisite for all business enterprises to run their IT operations smoothly. Colossal server farms are being built, currently running the Internet with complex business applications performing business progression analysis and server customer demands. These vast cloud data centers are also being used in developing business intelligence and innovative methods for enabling business communication across multinational enterprises working in parallel with other business firms [2].

On the other hand, to meet the increasingly high demand for e-commerce, the new digital economy is driving the mandate for data centers with masses of computers and other electronic equipment for hosting websites. Each data center contains rows of server frames, each frame housing various integrated assets such as servers, storage bricks, switches, and other specialized appliances. With such a complex environment of servers and other devices, the data centers are facing enormous real-time management challenges. Some of those include effectively managing utility costs, which are related to power, thermal management and CO_2 emissions [3]. These hi-tech servers with increased computational speeds account for higher heat wastage produced by a typical rack. The heat increases from each of these racks from 2005 onwards are estimated to be from 1 kW to as high as 12 kW. In 2019, a survey conducted by the Uptime Institute discovered that an average server rack with low density dissipated 12 kW, while the maximum recorded heat was almost 32 kW. Also, a much higher level of CO_2 emissions was calculated over the years due to increased demand for servers and the electricity required for the maintenance of these large cloud data centers worldwide [4].

Measuring power efficiency in cloud data centers has received significant attention recently as various power efficiency strategies and technologies are being developed, industrialized, and investigated to reduce the electricity usage below 73 billion kWh demand projected in 2020. In 2014 it was reported that the data centers with their high CO_2 emitting units like servers, switches, routers, storage components, cooling framework, and other such devices expend around 1.5% of global aggregate electricity [5] which accounts for up to 2% of worldwide CO_2 emissions from data industry alone [6]. By 2020, the data storage is expected to reach 30 ZB (1 Zettabyte = 10007 bytes), which points to more power consumption in data centers worldwide according to the research conducted by International Data Corporation (IDC) [7]. Another study done by Lawrence Berkeley National Laboratory (LBNL) estimated the power consumption of a typical data center to be between 120-940 W/m2. At the same time, a conventional office space consumes around a total of 50-100 W/m2 of power [8].

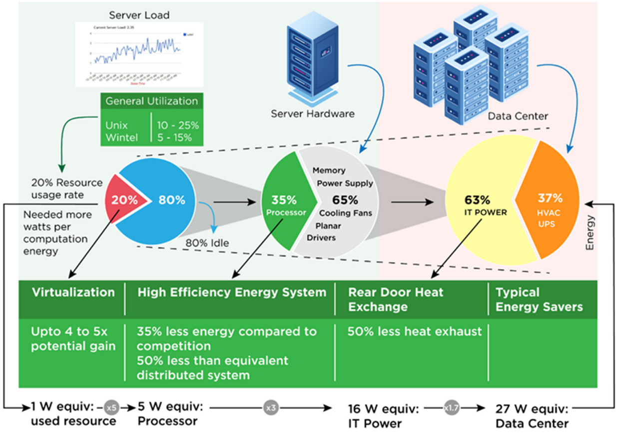


FIGURE 1. Power utilization in cloud level data center.

Figure 1 demonstrates that the power consumed in a tier level cloud data center is not only utilized by the IR component, i.e., the component responsible for performing the majority of the applications and tasks assigned; instead, it also shows that about 40% of the power is being used by various components like HVAC (Heating, Ventilating, and Air Conditioning) and UPS (Uninterruptible Power Supply). The IT component used only a fraction of the power, i.e., 30%, and is strictly used for computations performed mainly by servers and other IT related equipment. In contrast, the remaining power is used solely for power supply, fans, and drives, as shown in Figure 1. Previous researchers and vendors highlight that the IT part used for performing computational activities is highly underutilized, i.e., the power used to execute and process computational systems is much less than the servers' could support. It is, therefore, essential to understand, adopt and implement different power efficiency and power-related metrics to measure the use of power at the various phases of the power chain in numerous components of the tier level data center.

About half of 459 European companies are making considerable efforts to develop such strategies that inculcate green power solutions to their IT businesses while also saving costs to attain sustainable societies according to one of the reports published by IDC in 2008 [9]. Individual desktop PC users are not of such significant concern as are the data center managers whose excessive demand for power is escalating the costs. To study this trend, consider the growth size of the Google data center over the past few years. In 2000, the total number of computers at four different sites was around 6000 [10], which increased to 3200 servers at each site by the end of the year 2001 [7], [11]. In 2000, the power consumption

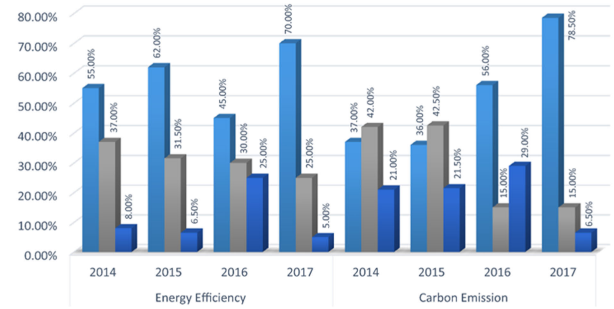


FIGURE 2. **Power efficiency and CO_2 emission in data centers [15].**

for each facility was assessed to be approximately 1.56 MWh (around 110,000 USD) per year [7], a kind of improvement expected in advanced power management solutions. The construction of an additional ten (10) new power plants will be required nationwide to meet this demand [12]. It is estimated that a single rack full of blade servers requires up to 25kW power to function.

Additionally, another 20-25kW power is required for cooling purposes which makes up for the peak electricity demand of around 30 homes in California [13]. Blade servers are plug-in cards housed in a chassis with many thin electronic circuit boards called blades. They are used for economical cost and power besides occupying less space [14]. The data for power efficiency and carbon emission for data centers in the year 2014-2017 has been shown in Figure 2.

The current statistics from the US as highlighted by Standard Performance Evaluation Corporation SPEC in 2016 emphasized that there are ∼14 million server machines currently deployed in various infrastructures in cloud data centers and this number will substantially increase to ∼18 million by 2020 [16]. According to SPEC, the average service life of a server is ∼4.4 years, and their power efficiency has increased from 17x since 2007. Peak power has held steady in 2007-2015 1S & 2S+ volume server average peak power is ∼330 Watts, the average power consumed by servers in the US today is ∼32 billion kWh/year and by 2019, it is projected to be ∼38 billion kWh/year [17].

A lot of metrics is currently available to evaluate the performance and efficiency of data centers, but one particular matrix turned into an accepted standard for the industry. The PUE metric conceived in 2006 and endorsed in 2007 by a non-profit IT organization called Green Grid is becoming popular for computing power efficiency in the data industry [18]. This article proposes a variant of previously available metrics from the Green Grid like PUE and DCIE called the Power Efficiency Measurement Calculator (PEMC) which not only measures power efficiency but also carbon footprints, CO_2 emissions from the tier-level data centers as they consume a tremendous amount of power. The carbon footprint measurement part of the proposed PEMC calculator comprises CO_2 emissions from both the local sources as well as from the power grid. Preferably, these carbon emissions are not only strong-minded from original power generation plants such as coal or gas that harvest more CO_2 than hydro or wind power plants, but also from other power sources like natural gas, diesel fuel, etc. The total emission value consists of all GHGs, such as CO_2 and methane (CH4). All these emissions need to be converted to CO_2 equivalents. The proposed measuring calculator helps:

- managers measure and further reduce the energy usage of data center IT infrastructure to achieve overall environmental sustainability,
- measure power efficiency in cloud data centers to enable a comparison between power-efficient and non- efficient data centers,
- help data center operators to improve the design and processes to achieve better efficiency,
- create tradeoff in measuring energy efficiency among various use-case scenarios, operating conditions, to accomplish better power efficiency,
- measure CO_2 emissions to improve data centers' sustainability, and
- identify a variant of previously available metrics from the Green Grid like PUE and DCIE called the Power Efficiency Measurement Calculator (PEMC)

The scope of this article is limited energy efficiency as the prosed PEMC calculator helps data center vendors and owners to reduce the energy consumptions of their data centers by measuring the energy used in their cloud data center infrastructures. The main focus was on developing a tool to measure power efficiency so we did not consider other factors like SLAs and QoS in our paper.

The rest of the paper is structured as follows. Section II describes the research background. Section III elaborates on related work done by other researchers, while Section IV explores the working of the proposed PEMC calculator. Section V describes the testing of the proposed calculator. Finally, Section VI provides conclusions.

II. PROBLEM BACKGROUND

Cloud data center infrastructure facilities and their associated networks play a vital role in enabling current ICT-enabled Internet enterprise giants such as Apple, Microsoft, Google, Facebook, YouTube and Amazon etc. to embrace cloud and IoT-enabled services and amenities through communication links to host various web-enabled applications, store data, and provide sharing and task execution services. These services require cloud data centers to consume massive amounts of power, which contributes greatly towards global electricity usage, thus increasing operational costs as well as generating an enormous amount of CO_2 emissions. The main reason behind this exponential growth in power consumption and operational costs is the continuous increase in the demand for increased computing and advancement in server technologies. One of the most important contemplations to reduce cloud data center operating costs and expenditures is to minimize power consumption, as it is directly pertinent to the carbon footprints. Therefore, it is imperative to develop

TABLE 1. CO_2 Emissions Climate Group and Global e Sustainability Initiative SMART 2020.

World	Emissions 2007 Mt CO_2e	Percentage 2007	Emissions 2020 Mt CO_2e	Percentage 2020
World	830	100%	1430	100%
Server Farms/ Data Centers	116	14%	257	18%
Telecom Infrastructure and Devices	307	37%	358	25%
PCs and Peripherals	407	49%	815	57%

latest power-saving technologies to measure and minimize data centers' continuous increased power demands to enable a sustainable and environment-friendly ecosystem as well as reduce the overall infrastructure and operational costs.

In this article, we focus on measuring power consumption, the cost of consumed power as well as CO_2 emissions in tier-level data centers by proposing a novel power efficiency measurement calculator and applying it in various case studies in different cloud data centers in Malaysia. In 2010, the Climate Group and GeSI investigated and published a report in which they broke down the potential hazardous environmental effects caused by the emission of CO_2 from cloud data centers on the digital global world as well as on global warming. The report predicts that the accumulated global carbon footprint from cloud data centers will reach the maximum value of approximately 260 million tons by 2020. This is almost thrice the size compared to 76 million tons of CO_2 predicted in 2003. These cloud data center emissions contribute to nearly 15 to 20% of the total ICT emissions. About 2% of the total global emissions are ICT-related CO_2 equivalent emissions, and data centers have a contribution of around 0.3% in the total aggregate emissions [7]. It has been observed that the IT industry's contribution is equivalent to the global aggregate CO_2 emissions than the total greenhouse gases from the aviation industry. It is also important to highlight that the intensification in these carbon emissions from the IT sector will likely increase from 3% of total global emissions in 2008 to a monstrous 6% by 2020 as shown in Table 1 [19].

The surge in the power consumption seen in data centers during 2007-2012 accounts for the increase in demand for high computational activities, high performance through equipment backups and redundancy, increased e-commerce and private clients [20]. Internet Data Corporation (IDC) asserts that by next year it would cost more to power the servers than to buy the servers [21]. US Department of Power has also declared that ''the power intake of a data center can be 100 times more than that of a typical commercial building''. However, s hardware vendors, policymakers and performance benchmarking companies have taken advanced step to address and reduce the total power consumption in today's data centers, as shown in Figure 3.

According to the experts from data center dynamics, the Global data center space requirement will be about 45.6 million sq. meters, an area bigger than the Netherlands. The overall Global data center power consumption will be more than 57.9 GW. The in-house facility investment will be approximately $194 billion, while the total global investment will exceed $280 billion dollars. They also predicted that Asia's data center space would be as ample as Europe's in terms of facilities, and as large as North America's in terms of investment [20]. The average power consumption was measured by using the following three values obtained from a pool of servers installed in the cloud data centers. These values are: (1) maximum power used by an average number of different categories of servers like blade servers, racks etc. (2) average server utilization ratio and (3) average server scalability ratio concerning the power consumed based on the utilization ratio of each sever installed in the cloud data center facility. These values will be represented in terms of watts of power consumed by server machines at their specific utilization ratios, as shown in Figure 4.

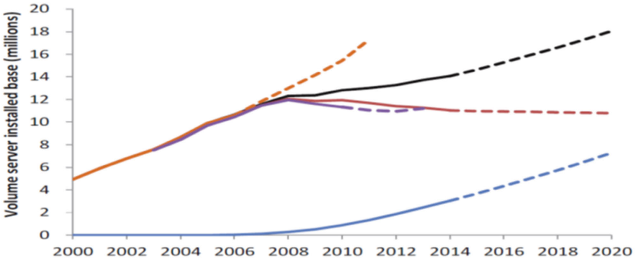


FIGURE 3. Total volume server installed base estimates from (2000-2020).

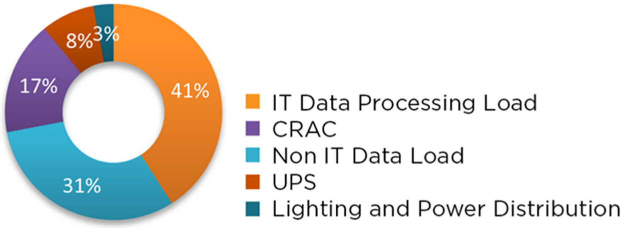


FIGURE 4. Breakdown of data center electrical requirements [6].

III. RELATED WORK

Inarguably, cloud data centers are the pivot of most enterprises ranging from small to large. The continuously changing business demands, conditions and requirements put more and more demand on the data center rack by rack. Nearly every cloud data center infrastructure, whether related to facility space, equipment implementations, software roll-outs, infrastructure upgrades or other areas of responsibility, revolves around the demand for more utilization through improved efficiencies. Every cloud infrastructure facility has various components such as electrical and mechanical equipment, IT systems with different types of server machines, storage and communication devices, network equipment like routers and switches etc. for performing a multitude of tasks. To accomplish this, cross-function data center managers are currently adopting smaller facility footprints, new architectures and infrastructure design concepts, and more power-efficient solutions in their tier-level cloud data center facilities. Power consumption is a censorious design parameter in modern cloud computing infrastructures and platforms [22]. A lot of research is being conducted to build power consumption models, develop power-aware cost models, manage workload fluctuations and other techniques are being investigated and researched to achieve an efficient trade-off between system performance and power cost.

Cloud data centers consume approximately 2% of the total electricity used in the United States; a typical cloud data center facility has more than 100 to 200 times the power usage intensity compared to a commercial structure. These sophisticated cloud facilities present tremendous opportunities for data center managers and their owners to reduce power usage to as much as about 80% between inefficient and efficient data centers. Based on the findings and solutions proposed by various researchers and vendors, the existing research performed on energy efficiency challenges and snags in the data center industry classifies them into four different categories such as (a) power management of the data center devices like CPU, disks, etc. (b) power management of data center systems [23]; (c) thermal management and approaches [24], [25] and (d) power consumption management in virtual fields [26], [27]. Moreover, a few researchers projected power efficiency or cost-effectiveness provisioning techniques for workloads [28], [29].

Most of the existing literature on power-saving technologies in the data center infrastructures clearly shows that there impedes lack of power efficiency metrics and calculators from applications to the infrastructure in cloud data centers. The problem with available measurement techniques is that they are time-consuming and costly to produce viable and feasible results. Power measurements should be calculated to incorporate the changes in power consumption caused by periodic workload fluctuations. Additionally, data centers are also continually changing their infrastructure components based on changing businesses, leading to ambiguous, inaccurate and out-of-date measurements. Green Grid, one of the pioneer vendors in measuring power efficiency, proposed and developed two metrics called Power Usage Effectiveness (PUE) and Data Center Infrastructure Efficiency (DCiE) [30], [31]. PUE got recognition as it measures the power efficiency related to IT components in the data center and is currently being used extensively in cloud data centers. Although PUE and DCiE are not difficult to implement they still lack computational intelligence while measuring power efficiency, as they involve numerous influencing variables [32].

Measuring the performance and productivity of a cloud data center is crucial as sub-optimal performance leads to different operational and financial implications for a cloud system. The overall performance of a typical cloud data center is measured as the total efficacy of the proposed system, including the throughput, response time, and the availability of services. Several factors must be considered while measuring the performance such as: distinction between substantial workloads, the overhead of performance measurements, power distribution losses, and measuring the power consumption at various levels of the data center. Several variants of PUE are proposed based on the industrial feedback; partial PUE was considered with a condition in which a specific segment of the facility was used in estimation. PUE was intended to be scalable to adjust variations in total power consumption with the changes in IT power load [33]. DCiE and PUE focus on IT equipment power utilization. As a step forward, another measurement calculator called Data Center Productivity (DCP) was proposed. It was designed to calculate the total power consumption of the data centers allotted to only the useful work produced [34]. Since the valuable work is measured in various ways, a family of metrics called DCxP was proposed in [35]. In summary, the majority of the existing calculators for power efficiency calculations available in the industry consider power consumption analysis based on the infrastructure of data centers without the application characteristics of different tier-level data centers and their usage. Also, the calculators from Green Grid and other vendors do not provide a mechanism where both power efficiency and carbon emissions are calculated at the same time using the same metrics.

In [36], two energy-aware algorithms were proposed to tackle the problem of Cloud datacenter high energy consumption. They had the advantage of being adaptive and taking into account the application types to ensure the maximum possible reduction of energy consumption. Also, they minimized the Service Level Agreement (SLA) violation rate. The first algorithm is responsible for dividing the hosts into four classes based on CPU utilization. This algorithm is highly adaptable to the dynamic workload generated by Cloud data centers since it uses a three- threshold framework instead of a two-threshold one. This algorithm is used for determining the value of the three thresholds. These values are determined adaptively to ensure low energy consumption and a minimal SLA violation rate. The second algorithm is responsible for VM placement with maximizing energy efficiency. The value of the three thresholds is input for the second algorithm and the output of the first algorithm. The proposed algorithms are more effective than other energy-aware algorithms because: 1: they use the adaptive three-threshold framework, 2: they consider CPU, memory, and workload types.

The energy consumption model in the Cloud data center is proposed in [37] by taking into accounts the following factors: NIC (Network Interface Card), application characteristics, processing unit, memory, disk, and energy consumption. Most of the existing approaches focus only on energy consumption and CPU and the other factors are ignored. The proposed model looks at the overall picture to come up with a holistic Cloud data center energy consumption model that achieves more than 95% prediction accuracy. Each factor contributing to the total energy consumption is analyzed using Principal Component Analysis (PCA) and regression methods.

A task-scheduling algorithm that is capable of load balancing and effective resource utilization is proposed in [38]. Greedy strategy and binding strategy are used in combination with task-pairing to perform an effective scheduling algorithm that increases users' service quality and reduces the average response time. Moreover, besides the service quality, the task priority is also considered at the same time. Using the proposed algorithm, the total task completion time is significantly shortened. However, taking into account multiple factors such as the system's energy consumption and the network-wide band, can be added to the task scheduling algorithm to increase the performance.

To further enhance the work proposed in [38] and take it to the next level, a novel algorithm named ITSA (Improved Task Schedule Algorithm) is proposed in [39]. Compared to other algorithms, ITSA significantly improves the performance in terms of load balancing and QoS. An unbalanced workload problem is handled using the gain value of task swap by putting the task with the minimum gain value and the one with the maximum gain value together, "task pair", and scheduling by adopting the greedy strategy. The ITSA algorithm achieves the best performance in terms of the degree of workload balancing (compared to other algorithms).

In [40] energy-mindful calculations proposed to improve the energy effectiveness and limit the SLA infringement in the cloud climate. The recreation results show that concerning the energy effectiveness, the Gdr have over-burden recognition calculation improving energy utilization better then the MCP calculation and during the VM choice from over-burden have thought about CPU, memory, and organization traffic factor is more compelling than a solitary factor. The results also show that proposed algorithm decreases the energy consumption and maintain the required performance levels in a cloud center.

The Cloud server all around the globe are developing and the demand for computing is increasing rapidly. Hence, to run these servers, a huge amount of electric energy is required which lead to high operational expense furthermore, high CO_2 discharge. The high discharge of CO_2 is a straightforwardly terrible effect on the social climate of the earth. In this work authors proposed MuMs VMs determination strategy, which is useful to limit the electric energy utilization through the SLA violation of the cloud server centers. In the execution of this arrangement, the authors utilized the CloudSim test system to acquire the investigation results for examination and correlation with other old calculations [41].

To overcome the problems of Particle swarm optimization, (PSO) algorithms in networked data centers such as low-quality initial particle swarm, and take its advantages such as high precision easy implementation and fast convergence, it is combined with opposition-based learning (OBL) and tentative perception (TP) in [42] to propose a method called OBL–TP–PSO. This algorithm optimizes cloud computational task scheduling efficiently. OBL–TP–PSO is capable of finding the optimal solution at a minimum number of iterations compared with existing task algorithms. OBL is used to improve the quality of the initial particle swarm, while the TP method is used to search for the individual optimum around each particle. The OBL–TP–PSO algorithm enhances the following performance indicators: quality of service, total execution time and load balancing.

This article overcomes the research challenges of PUE and DCiE metrics and proposes a novel power efficiency and CO_2 measuring calculator called PEMC that uses PUE as underlying metrics to define power efficiency and enhance power efficiency management optimization along with measuring the CO_2 emissions to make the data center industry more environmentally friendly and power efficient.

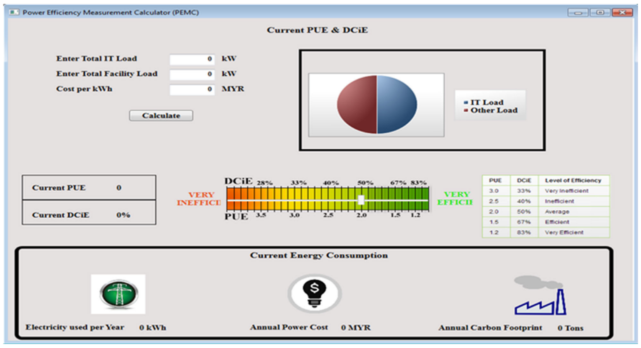
IV. PROPOSED CALCULATOR FOR POWER USAGE MEASUREMENT AND CO_2 EMISSION (PEMC)

The data center industry must accomplish power proportionality and efficiency at the installed server volume level or an entire data center level by dynamically scheduling and shifting the processes and jobs among server machines using various techniques such as server virtualization and consolidations to realize the power dissipation versus server utilization curve at the server level. The emphasis should be on the realization of power-proportional operations that can be achieved by implementing idle low power modes for underutilized server machines. Additionally, the ever-increasing power consumption of computing systems has started to limit performance efficiency due to overwhelming electricity bills and CO_2 footprints. It is, therefore, agreed that the design of the computing system infrastructures should be altered and shifted to power efficiency, and it becomes imperative to define techniques, programs, and procedures for enabling and achieving this power efficiency. The power efficiency of a computing system is defined as the ratio of useful work done to the total power distributed to the system. For data centers, power efficiency translates into the useful work performed by different subsystems.

In this article, research is being conducted to propose and design a novel PEMC calculator based on PUE metrics to improve the efficiency and performance of data centers to make them power-efficient and green. This article introduces a new power efficiency measurement calculator called the Power Efficiency Measurement Calculator (PEMC). It uses a comprehensive technique to help data center managers measure the performance and efficiency of their data centers and considers the following key points for attaining power efficiency:

- Power infrastructure such as Uninterruptible power supplies (UPS), power distribution units (PDUs),
- Cooling equipment such as free cooling, variable-speed drives (VSDs), temperature and humidity,
- Airflow management such as hot aisle/cold aisle, containment, grommets and
- Information technology (IT) efficiency such as a server, storage and network virtualization.

Currently, power efficiency measurement is considered the foremost step for data center policymakers to develop and



Power Efficiency Measurement Calculator (PEMC)

Current PUE & DCiE

Enter Total IT Load 0 kW
Enter Total Facility Load 0 kW
Cost per kWh 0 MYR

Current PUE 0
Current DCiE 0%

PUE	DCiE	Level of Efficiency
3.0	33%	Very Inefficient
2.5	40%	Inefficient
2.0	50%	Average
1.5	67%	Efficient
1.2	83%	Very Efficient

Current Energy Consumption

Electricity used per Year 0 kWh
Annual Power Cost 0 MYR
Annual Carbon Footprint 0 Tons

FIGURE 5. Proposed Power Efficiency Measurement Calculator (PEMC).

implement new initiatives and mechanisms to determine the efficiency of their cloud data centers. The proposed PEMC calculator, as shown in Figure 5, helps to measure:

- PUE and DCIE calculations
- Total costs incurred
- CO_2 emissions

A. POWER USAGE EFFECTIVENESS (PUE) CALCULATION

Several industries and research organizations proposed different metrics and calculators to assess the power consumption and overall performance of data centers and their operating costs [43]. The European CoC measures data center efficiency by using Power Usage Effectiveness (PUE) [34] as adopted by the industry. It has been considered as an efficient power efficiency measuring metric by the majority of data center operators as it helps to achieve data center efficiency, which eventually empowers environmental sustainability. It should be used to determine various effects, designs and operational decisions within a specific facility to assess rising trends in an individual data center over a period of time. The higher the PUE value, the lower the efficiency of the facility, as more 'overhead' energy is consumed for powering the electrical load. The ideal PUE value is one (1), which indicates the maximum attainable efficiency with no overhead. It is not feasible at present due to the consumption of electricity by UPS, fans, pumps, transformers, lighting, and other auxiliary equipment in addition to the consuming IT load [44]. PUE is defined as the ratio of total data center power input to the power consumed by the IT equipment in the cloud data center as given by the following equation 1 [44].

$$PUE = \frac{Total\ Facility\ Load}{Total\ IT\ \ Load} \tag{1}$$

In PUE, the total facility load refers to overall electricity consumption by general equipment in the data centers, including servers, network routers, cooling systems, lighting, etc. Whereas, the total IT load is the whole power usage of IT equipment in the data center. This metric is useful for determining the level of efficiency for data centers. A PUE range of 1.2-2.0 is considered a high level of efficiency. For example, if the PUE calculated value is 3.0; that means that in a data center the power utilization of all facilities is three times more than the energy usage of the IT equipment [45].

B. DATA CENTER INFRASTRUCTURE EFFICIENCY (DCiE) CALCULATION

The DCiE metrics values are not fixed for each cloud data center facility; instead, these values vary depending on IT electrical load, which is a variable and site-specific function of the IT software, architecture, hardware, load, and efficiency. DCiE calculates data center power efficiency by using equation 2.

$$DCIE = \frac{Total\ IT\ \ Load}{Total\ Facility\ Load} \times 100 \tag{2}$$

The variability in the DCiE results leads to ambiguous and incorrect results which make these metrics not suitable for predicting the impact of changes in the data center. DCiE is not a measure on which decisions or plans should be based as it does not contain any specific information to separate the sThis metric is useful only when measuring the performance of power-efficient data centers; it is desired as it validates the percentage of efficiency level in server machine farms. DCiE represents a reverse value of PUE by multiplying it by 100. For instance, if the value of DCIE is estimated to be 33%, it demonstrates that the level of efficiency in the data center is very low [16]. Table 2 shows the level of efficiency of data centers based on PUE and DCIE.

TABLE 2. Level of efficiency of data centers based on PUE and DCIE [46].

PUE	DCiE	Level of Efficiency
3.0	33%	Very Low
2.5	40%	Low
2.0	50%	High
1.5	67%	Very High
1.2	83%	Highest

C. CARBON FOOTPRINT IN DATA CENTERS

The carbon footprint and greenhouse gases are central for the future of our society and therefore becoming subject to governmental regulations and taxes. As a result, the "greenness" of a data center is becoming increasingly important. A green energy-efficient data center is an IT facility with mechanical, lighting, electrical and IT equipment arranged and placed for maximum power efficiency and minimum environmental impact. The influence and effects of generating a significant amount of CO_2 emissions also contribute towards the emergence of environment-friendly and green IT and non-IT devices for the design, implementation, operation, and processing of cloud data centers as shown in Figure 6. Currently, the carbon and power issues and challenges are making international headlines with increased frequency. Governments, non-profit organizations, and corporations are conducting research studies to analyze their carbon footprint regularly. The immediate goal is to measure the impact of their activities on global warming and to establish action plans that

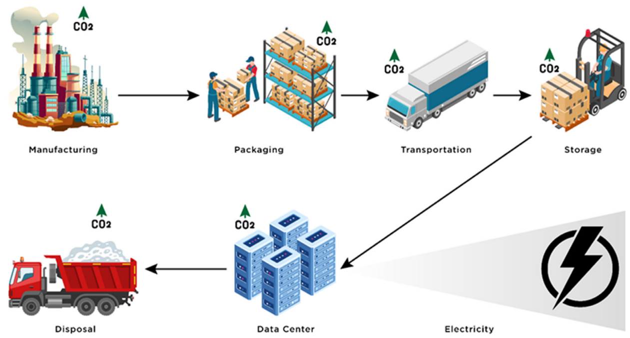


FIGURE 6. Carbon-producing phases of the product life cycle of a data center.

reduce carbon emissions. In the year 2007, the data centers in Western Europe consumed a whopping 56 terawatt-hours (TWh) of power per year. According to the EU, these values will almost double to 104 TWh by 2030. This projected growth, if not countered by efficient energy management, will create more real problems for data center operators as well as prevent European Union from achieving its overall carbon reduction and climate change targets [47], [48].

D. WORKING OF PROPOSED PEMC CALCULATOR

The increasing usage of cloud-enabled infrastructures is pushing the data center industry towards a more efficient and reduced power consumption model with minimized carbon footprints. Data center deployments often take longer to complete than other types of power efficiency engagements. All power efficiency-related equipment and infrastructures require careful planning and execution and may delay and complicate the overall power and cost savings in cloud data centers. It further leads to incomplete IT projects with enormous costs incurred. Appropriate efficiency evaluations in applying power-saving techniques can dramatically achieve better results while upgrading IT infrastructures. The power-efficient designs for computing devices such as servers, routers, and switches that have a direct effect on power usage, could make a data center greener [49].Understanding power consumption patterns is necessary for its improvement. Servers consume a more substantial fraction of power in cloud environments, and their power consumption varies with utilization. This consumption also varies with the type of computational processing performed in cloud data centers. The proposed PEMC calculator uses the PUE and DCiE metrics to measure the energy efficiency in tier-level data centers, as given in the pseudocode below.

```
Start
  1) Define function calculator with attributes TotalFacilityPower, ITEquipmentPower & cost
  2) Divide TotalFacilityPower by ITEquipmentPower // PUE
  3) Store output of step 3 into PUE variable
  4) Divide ITEquipmentPower by TotalFacilityPower // DCiE
  5) Store output of step 5 into DCiE variable
  6) Multiple DaysInYear,HoursInDay & TotalFacilityPower together
  7) Store output of step 7 into AnnualPowerUsage Variable
  8) Multiply AnnualPowerUsage with cost
  9) Store the step 9 output in AnnualPowerCost Variable // Total power usage in a Data Center
 10) Multiply TotalFacilityPower*$CO_2$Emissions
 11) Store output of step 11 in AnnualCarbonFootprint Variable // $CO_2$ emissions
 12) Return PUE, DCiE, AnnualPowerUsage, AnnualPowerCost & AnnualCarbonFootprint
 13) Initialize variable TotalFacilityLoad, ITEquipmentLoad & cost
 14) Take input TotalFacilityLoad, ITEquipmentLoad & cost
 15) Call Function calculator and pass attributes TotalFacilityLoad, ITEquipmentLoad & cost
 16) Store the output of step 16 in the following variables: PUE, DCiE, AnnualPowerUsage, AnnualPowerCost, AnnualCarbonFootprint
 17) Print PUE, DCiE, AnnualPowerUsage, AnnualPowerCost, AnnualCarbonFootprint
End
```

The PEMC calculator calculates total annual power usage based on the values given in equations 3 and 4. It also calculates CO$_2$ emissions in the data center by applying the formula, as shown in equation 5. These equations are taken from the algorithm and pseudocode used to calculate power efficiency as well as CO$_2$ emissions separately. In order to explain the working of the proposed algorithm in details, we have converted the coding functionality into these 3 equations. In addition, these equations show how to calculate annual power consumption per year. They use the value of the total facility load of a data center, including a load of components and equipment such as cooling systems, server machines, routers, switches, etc. and lighting as given in equation 3 below.

$$\begin{aligned}&\mathit{Electricity\ Used\ per\ Year}\\&\quad = (\mathit{Total\ Facility\ Load\ per\ Year}) \times 365 \times 24 \qquad (3)\end{aligned}$$

The usage of IT devices in data centers is increasing. The upcoming generation of ICT has green designs, which do mean not only a green environment but also green economics to help reduce power cost in data farms. The equation below shows how power consumption per year is calculated as given in equation 4.

$$\begin{aligned}&\mathit{Annual\ Power\ Cost}\\&\quad = (\mathit{Electricity\ Used\ per\ Year}) \times \mathit{Cost} \qquad (4)\end{aligned}$$

The value of annual power costs is calculated based on the unit cost of power usage of all the equipment, such as cooling systems, servers, routers, and lighting. For instance,, based on the Tenaga National sources, the value of a unit cost for commercial sectors in Malaysia is 0.39 Ringgit [50].

In this research, the carbon emissions produced by the power consumption in the data center industry are discussed as one of the major problems. The carbon footprint is calculated based on carbon emissions produced per kilowatt-hour of electricity. For calculating the annual carbon emission, the emission factor is a key value. It is a fixed value and the amount of this factor is 6.89551 × 10-4 metric tons CO_2 / kWh. This factor is defined as the CO_2 output emission rate per year for each data center [51], as given in equation 5

$$\begin{aligned} &Annual\ Carbon\ Footprint \\ &\quad = (Electricity\ Used\ per\ Year) \times Emission\ Factor \end{aligned} \tag{5}$$

According to the latest research, the emission factor rate is used to calculate the carbon footprint in data centers [52]. Figure 7 shows recent research on the production of carbon footprint in Apple's data center. For all the facilities, this value is 2%, which means CO_2 emissions have increased in recent years, although using renewable energy for facilities has improved in this company [48].

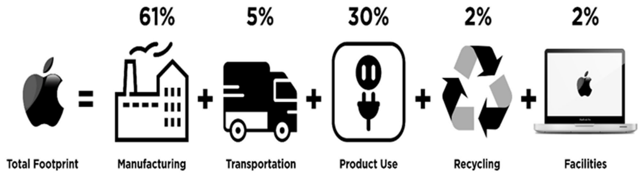


FIGURE 7. CO_2 **emissions in the Apple Industry [53].**

The working of the proposed PEMC calculator is given in Figure 8, where PUE and DCiE values are calculated based on equations 1 and 2 given and explained above. The functionality of the proposed PEMC calculator is given in the following code as it defines the major functions of calculating energy efficiency, CO_2 emissions, and the total power costs incurred in the cloud data centers. The following listing describes the working of different functions in the PEMC Calculator

V. TESTING OF POWER EFFICIENCY MEASUREMENT CALCULATOR PEMC

The proposed calculator was tested and validated by applying it in a case study performed on a tier-level data center at Asia Pacific University Kuala Lumpur. The main objective was to perform both Unit Testing for testing the individual components of the proposed calculator and User Acceptance Testing to ensure that the proposed system meets user satisfaction and the level of functionality.

A. SIMULATION PARAMETERS

For measuring power-efficiency and CO_2 emissions, different metrics such as PUE, DCiE, and DCP already exist but our proposed PEMC calculator calculates all these values in single metrics. In order to evaluate the performance of the proposed PEMC calculator, different parameters were selected as given in table 3 based on [54].

```
def calculator(TotalFacilityPower,
    ↪ ITEquipmentPower,cost):
PUE=TotalFacilityPower/ITEquipmentPower
DCiE=ITEquipmentPower/TotalFacilityPower
AnnualPowerUsage=365*24*
    ↪ TotalFacilityPower
AnnualPowerCost=AnnualPowerUsage*cost
AnnualCarbonFootprint=TotalFacilityPower
    ↪ *5.3
return PUE,DCiE,AnnualPowerUsage,
    ↪ AnnualPowerCost,
    ↪ AnnualCarbonFootprint
TotalFacilityLoad=float(input("Enter
    ↪ Total Facility Load : "))
ITEquipmentLoad=float(input("Enter IT
    ↪ Equipment Load : "))
cost=float(input("Enter Cost : "))
PUE,DCiE,AnnualPowerUsage,
    ↪ AnnualPowerCost,
    ↪ AnnualCarbonFootprint=calculator(
    ↪ TotalFacilityLoad,ITEquipmentLoad,
    ↪ cost)
print("Current PUE : "+str(PUE)+"\
    ↪ nCurrent DCiE : "+str(DCiE)+"\%\
    ↪ nAnnual Power Usage : "+str(
    ↪ AnnualPowerUsage)+"KW/h\nAnnual
    ↪ Power Cost : "+str(AnnualPowerCost
    ↪ )+"MYR\nAnnual Carbon Footprint :
    ↪ "+str(AnnualCarbonFootprint)+"Tons
    ↪ ")
```

Listing 1. Working of different Functions in PEMC Calculator.

TABLE 3. Test scenario.

Entities	Number
Host	200
VM	80
User	1
VMM	Xen
Bandwidth	20 GB
Processor frequency	3530,2024,2600,2333
RAM	8 GB
Number of CPU	1
Operating System	Linux
Host specification	Asia Pacific
Host specification	
Processor frequency	2.8 GHZ; 2.6 GHZ
RAM	16 GB
Storage	50 GB
Cores per processor	4
Operating system	Linux

B. RESULTS

To test each part, the data was collected from the data center managers using interviews. These were conducted in a formal way using a questionnaire prepared according to the

TABLE 4. Average cost of power for all facilities in data center.

Main Equipment	Unit Number	Unit Load per Hour / kWh	Load per Hour / kWh	Unit Cost of Power (kWh/RM)	Total Monthly Cost of Power (RM)
Server	5	0.85	4.25	0.33	1,193
Router	5	0.42	2.1	0.33	590
Switch	20	0.14	2.76	0.39	775
Cooling System	1	3.5	3.5	0.33	983
Lighting System	10	0.02	0.22	0.33	62

TABLE 5. Average cost of power for IT facilities.

Main Equipment	Unit Number	Unit Load per Hour (kWh)	Load per Hour (kWh)	Unit Cost of Power (kWh/RM)	Total Monthly Cost of Power (RM)
Server	5	0.85	4.25	0.39	1,193
Router	5	0.42	2.1	0.39	590
Switch	20	0.14	2.76	0.39	775

TABLE 6. PUE values provided by APU data center manager.

Test ID	1		
Date	21th July 2019		
Type of Testing	Unit Testing		
Objective of Testing	Evaluate PUE Value		
Prerequisite	The value of Total IT Load and Total Facility Load must be available.		
Test No.	***Data for Testing***	***Actual Output***	***Expected Output***
1	Total IT Load = 24000 Total Facility Load = 48000	The Value of PUE is 2.0	The Value of PUE is 2.0
2	Total IT Load = 57000 Total Facility Load = 33000	Admin will see error “Total IT Load the value must be less than or equal to the Total Facility Load”	Admin will see error “Total IT Load the value must be less than or equal to the Total Facility Load”
3	Total IT Load = 0 Total Facility Load = 59000	Admin will see error “Total IT Load value must be greater than zero!”	Admin will see error “Total IT Load value must be greater than zero!”
4	Total IT Load = 0 Total Facility Load = 43000	Admin will see error “Total IT Load value entered is not a number”	Admin will see error “Total IT Load value entered is not a number”

requirements of testing the proposed calculator. The data was also collected from Datasheets of electrical devices and Tenaga Nasional Berhad (TNB) electric utility company in Malaysia which are used to supply electrical power to the designated data center and the devices installed inside it. Table 5 shows that the electrical data such as unit number, unit load per hour/kWh, load per jour/kWh, the unit cost of energy (kWh/RM) and the total monthly cost of energy (RM) were collected from data sheets and TNB sources. For example, a unit load of one server was between 500 to 1,200 watts per hour [55]. So, 850 watts for every hour is the normal power utilization for one server, which equals 0.85 kWh. By turning off some of the main servers during peak off-hours will also decrease the amount of electricity, thus reducing the power cost per kWh/RM [56], [57]. Table 4 shows the total monthly power consumption cost for all the facilities for each equipment and unit loads per hour.

If administrators reduce the number of hours or amount of energy usage in data centers for each facility, they can reduce the total energy costs and save money. Table 5 shows the monthly energy usage cost of IT equipment. Cisco Catalyst 3750E-48PD was used as a switch, as this model has reduced energy consumption compared to other models. This switch has an average electricity consumption of 0.14 KW per hour [58].

The unit load values shown in Table 6 are taken from the total number of installed network devices in the APU data center which comprises routers, switches, server machines, and network and storage devices. The load per hour is the result of a unit load multiplied by the unit number. The unit cost of power shows the price of power per KWh as described by TNB (Tenaga Nasional Berhad) Malaysia. The total monthly power usage cost is calculated by multiplying the unit cost of energy with load per hour, times 24 (hours per day), and times 30 (days per month) [59]. The IT and facility electricity usage was the input data for PEMC. The data center manager was responsible for measuring the values and writing them down for comparison purposes to check the efficiency of the proposed calculator.

The operation of the system and all its processes, even each small unit of source code was examined separately [6], [43], [60]. Table reftab5 shows the actual and expected output of PUE values based on the different amounts of IT and facility load. The data for testing was examined in four steps. In the first step, 50% of the entire facility load was considered the total IT load. It is essential to highlight that if the total IT load is considered Zero (0), the system will show an error; therefore, the ‘Total IT load value must be greater than 0’. PEMC was tested in four (4) different scenarios with various input parameter values, as shown in Table 6. The data center

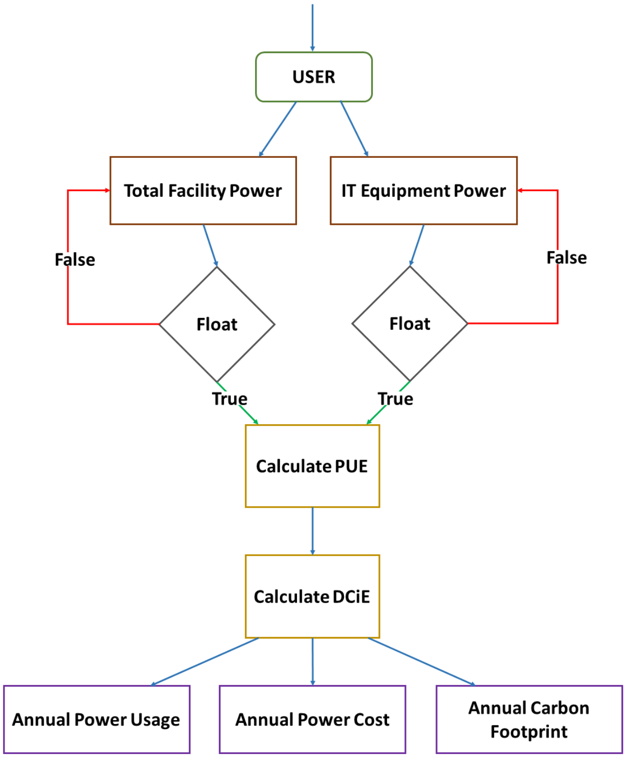


Figure 8. Working of proposed PEMC Calculator.

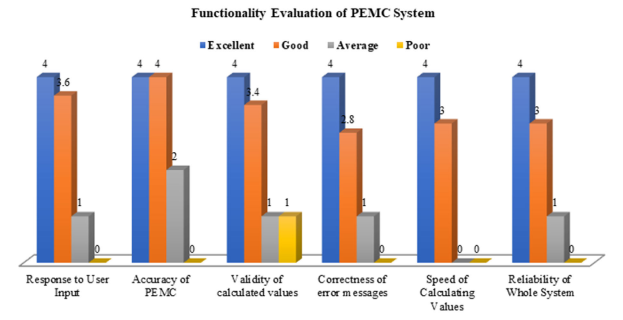


Figure 9. Functionality Analysis Diagram of PEMC Calculator.

manager input the parameter values in the calculator to check its error recognition and functionality. The results obtained from the PEMC calculator demonstrate that it performed very well and did not give any error while processing and executing the input values.

Figure 9 shows network administrators' feedback about the functionality of the PEMC system. The result shown is based on the functional evaluation of different variables used to test the technical and operational requirements of PEMC. The calculator was tested at a few small-medium data centers. The results obtained from various data center managers demonstrate the accuracy of PEMC, as the response to user input and the validity of the proposed calculator is excellent compared to the metrics available in the literature. Its accuracy and reliability can be seen using the ratings shown in Figure 9. It demonstrates that the proposed calculator was adored by most of the data center managers. Even though the correctness of error, the speed of calculations and reliability are rated a bit low, it is competent enough to be applied to different data centers. Responses to user input and the validity of the calculated values are considered as second and third essential features for our proposed calculator. Based on the collected information from more than (10) ten data center managers, it was concluded that the user interface of the proposed PEMC calculator meets user satisfaction and the GUI has been accepted. Moreover, the level of functionality also justifies the desired standardized values given in the evaluation forms, and most data center managers have shown a willingness to use the proposed PEMC calculator for calculating the power efficiency and CO_2 emission values of their data centers to make them power efficient and environment-friendly.

VI. CONCLUSION

In this article, we have proposed a PEMC calculator which takes into consideration many features and delivers more benefits when compared with other metrics and approaches found in the literature. The proposed PEMC calculator includes the capacity to periodically measure the overall performance and efficiency of cloud data centers and allow the administrators to determine the exact utilization of computing, storage, network resources and their appropriate power consumption. Our proposed technique for the PEMC metric also combines and integrates the measurement of the CO_2 emissions at the same time, thereby reducing the costs and complexity involved in using a different technique. We have demonstrated that our proposed calculator can be highly useful in assisting administrators to exactly calculate the costs incurred per kWh/RM for individual and overall data center facilities. We have shown that our proposed calculator is not only easy to use but also cost-effective which can be used in all tier-level data center levels.

REFERENCES

[1] H. M. Makrani, S. Rafatirad, A. Houmansadr, and H. Homayoun, "Main-memory requirements of big data applications on commodity server platform," in *Proc. 18th IEEE/ACM Int. Symp. Cluster, Cloud Grid Comput. (CCGRID)*, May 2018, pp. 653–660.

[2] R. Bose and X. Luo, "Integrative framework for assessing firms' potential to undertake green IT initiatives via virtualization—A theoretical perspective," *J. Strategic Inf. Syst.*, vol. 20, no. 1, pp. 38–54, Mar. 2011.

[3] M. Uddin, A. A. Rahman, and J. Memon, "Carbon sustainability framework to reduce co2 emissions in data centres," *Int. J. Green Econ.*, vol. 5, no. 4, pp. 353–369, 2011.

[4] Uptime Institute. (2019). *Uptime Institute Report: Annual Data Centre Survey Results*. [Online]. Available: https://datacenter.com/wp-content/uploads/2019/06/data-center-survey-2019.pdf

[5] M. Hanini, S. E. Kafhali, and K. Salah, "Dynamic VM allocation and traffic control to manage QoS and energy consumption in cloud computing environment," *Int. J. Comput. Appl. Technol.*, vol. 60, no. 4, pp. 307–316, 2019.

[6] C. Fiandrino, D. Kliazovich, P. Bouvry, and A. Y. Zomaya, "Performance and energy efficiency metrics for communication systems of cloud computing data centers," *IEEE Trans. Cloud Comput.*, vol. 5, no. 4, pp. 738–750, Oct. 2017.

[7] A. Shehabi, S. Smith, D. Sartor, R. Brown, M. Herrlin, J. Koomey, E. Masanet, N. Horner, I. Azevedo, and W. Lintner, "United States data center energy usage report," Lawrence Berkeley Nat. Lab., Berkeley, CA, USA, Tech. Rep. LBNL-1005775, 2016.

[8] Standard Performance Evaluation Corporation. (2014). *Specpower_ssj2008 Run and Reporting Rules*. [Online]. Available: http://www.spec.org/power/docs/SPECpower_ssj2008-Run_Reporting_Rules.html

[9] L. M. Hilty and B. Aebischer, *ICT Innovations for Sustainability*, vol. 310. Cham, Switzerland: Springer, 2015.

[10] R. Zhou, Y. Shi, and C. Zhu, "AxPUE: Application level metrics for power usage effectiveness in data centers," in *Proc. IEEE Int. Conf. Big Data*, Oct. 2013, pp. 110–117.

[11] L. Wang and S. U. Khan, "Review of performance metrics for green data centers: A taxonomy study," *J. Supercomput.*, vol. 63, no. 3, pp. 639–656, Mar. 2013.

[12] *Epa Energy Star Program Requirements for Computer Systems–Draft 4*, EPA, Washington, DC, USA, 2009.

[13] I. H. Cheung, S. Greenberg, R. Mahdavi, R. Brown, and W. Tschudi, "Energy efficiency in small server rooms: Field surveys and findings," Lawrence Berkeley Nat. Lab., Berkeley, CA, USA, Tech. Rep. 500F10F052, 2014.

[14] S. El Kafhali and K. Salah, "Modeling and analysis of performance and energy consumption in cloud data centers," *Arabian J. Sci. Eng.*, vol. 43, no. 12, pp. 7789–7802, Dec. 2018.

[15] M. Uddin, Y. Darabidarabkhani, A. Shah, and J. Memon, "Evaluating power efficient algorithms for efficiency and carbon emissions in cloud data centers: A review," *Renew. Sustain. Energy Rev.*, vol. 51, pp. 1553–1563, Nov. 2015.

[16] M. Avgerinou, P. Bertoldi, and L. Castellazzi, "Trends in data centre energy consumption under the European code of conduct for data centre energy efficiency," *Energies*, vol. 10, no. 10, p. 1470, Sep. 2017.

[17] K.-D. Lange, M. G. Tricker, J. A. Arnold, H. Block, and S. Sharma, "Server efficiency rating tool (SERT)," in *Proc. 3rd Joint WOSP/SIPEW Int. Conf. Perform. Eng. (ICPE)*, 2012, pp. 255–256.

[18] The Green Grid. (2008). *A Framework for Data Centre Power Productivity*. [Online]. Available: https://www.greenbiz.com/sites/default/files/document/GreenGrid-Framework-Data-Center-Energy-Productivity.pdf

[19] S. Ruth, "Reducing ICT-related carbon emissions: An exemplar for global energy policy?" *IETE Tech. Rev.*, vol. 28, no. 3, pp. 207–211, 2011.

[20] Magazines Data Centre Dynamics. (2020). *The Business of Data Centres*. [Online]. Available: https://www.datacenterdynamics.com/en/magazine/

[21] International Data Corporation. (2020). *Worldwide Quarterly Server Tracker*. [Online]. Available: https://www.idc.com/getfile.dyn?containerId=IDC_P348&attachmentId=47389428

[22] G. Grid, "Harmonizing global metrics for data center energy efficiency, global taskforce reaches agreement regarding data center productivity," Green Grid Consortium, Beaverton, OR, USA, Tech. Rep., 2014.

[23] V. Avelar, D. Azevedo, A. French, and E. N. Power, "PUE: A comprehensive examination of the metric," Green Grid, Beaverton, OR, USA, White Paper 49, 2012, vol. 49.

[24] X. Jin, F. Zhang, L. Wang, S. Hu, B. Zhou, and Z. Liu, "Joint optimization of operational cost and performance interference in cloud data centers," *IEEE Trans. Cloud Comput.*, vol. 5, no. 4, pp. 697–711, Oct. 2017.

[25] W. Wu, W. Lin, and Z. Peng, "An intelligent power consumption model for virtual machines under CPU-intensive workload in cloud environment," *Soft Comput.*, vol. 21, no. 19, pp. 5755–5764, Oct. 2017.

[26] Y. Gao and L. Yu, "Energy-aware load balancing in heterogeneous cloud data centers," in *Proc. Int. Conf. Manage. Eng., Softw. Eng. Service Sci. (ICMSS)*, 2017, pp. 80–84.

[27] C. de Alfonso, M. Caballer, F. Alvarruiz, and G. Moltó, "An economic and energy-aware analysis of the viability of outsourcing cluster computing to a cloud," *Future Gener. Comput. Syst.*, vol. 29, no. 3, pp. 704–712, Mar. 2013.

[28] R. S. Tucker, "Energy consumption modelling of coherent transmission in data centers," in *Proc. Opt. Fiber Commun. Conf.*, 2019, p. 1, Paper W1F-1.

[29] T. Thein, M. M. Myo, S. Parvin, and A. Gawanmeh, "Reinforcement learning based methodology for energy-efficient resource allocation in cloud data centers," *J. King Saud Univ.-Comput. Inf. Sci.*, pp. 1–13, Nov. 2018.

[30] *Enabling the Low Carbon Economy in the Information Age*, S. GeSI, Report Climate Group Behalf Global eSustainability Initiative, Brussels, Belgium, 2008.

[31] T. Lin, T. Alpcan, and K. Hinton, "A game-theoretic analysis of energy efficiency and performance for cloud computing in communication networks," *IEEE Syst. J.*, vol. 11, no. 2, pp. 649–660, Jun. 2017.

[32] J. Zhan, L. Wang, X. Li, W. Shi, C. Weng, W. Zhang, and X. Zang, "Cost-aware cooperative resource provisioning for heterogeneous workloads in data centers," *IEEE Trans. Comput.*, vol. 62, no. 11, pp. 2155–2168, Nov. 2012.

[33] B. Pati, J. L. Sarkar, and C. R. Panigrahi, "ECS: An energy-efficient approach to select cluster-head in wireless sensor networks," *Arabian J. Sci. Eng.*, vol. 42, no. 2, pp. 669–676, Feb. 2017.

[34] Toolbox Tech. (2014). *S. Tuf Power Usage Effectiveness*. [Online]. Available: https://it.toolbox.com/

[35] J. Koomey, "Growth in data center electricity use 2005 to 2010," New York Times, vol. 9, p. 161, 2011.

[36] Z. Zhou, J. Abawajy, M. Chowdhury, Z. Hu, K. Li, H. Cheng, A. A. Alelaiwi, and F. Li, "Minimizing SLA violation and power consumption in cloud data centers using adaptive energy-aware algorithms," *Future Gener. Comput. Syst.*, vol. 86, pp. 836–850, Sep. 2018.

[37] Z. Zhou, J. H. Abawajy, F. Li, Z. Hu, M. U. Chowdhury, A. Alelaiwi, and K. Li, "Fine-grained energy consumption model of servers based on task characteristics in cloud data center," *IEEE Access*, vol. 6, pp. 27080–27090, 2018.

[38] Z. Zhou, H. Xie, and F. Li, "A novel task scheduling algorithm integrated with priority and greedy strategy in cloud computing," *J. Intell. Fuzzy Syst.*, vol. 37, no. 4, pp. 4647–4655, Oct. 2019.

[39] Z. Zhou, H. Wang, H. Shao, L. Dong, and J. Yu, "A high-performance scheduling algorithm using greedy strategy toward quality of service in the cloud environments," *Peer-Peer Netw. Appl.*, vol. 13, pp. 1–10, Feb. 2020.

[40] R. Yadav, W. Zhang, O. Kaiwartya, P. R. Singh, I. A. Elgendy, and Y.-C. Tian, "Adaptive energy-aware algorithms for minimizing energy consumption and SLA violation in cloud computing," *IEEE Access*, vol. 6, pp. 55923–55936, 2018.

[41] R. Yadav, W. Zhang, H. Chen, and T. Guo, "MuMs: Energy-aware VM selection scheme for cloud data center," in *Proc. 28th Int. Workshop Database Expert Syst. Appl. (DEXA)*, Aug. 2017, pp. 132–136.

[42] Z. Zhou, F. Li, J. H. Abawajy, and C. Gao, "Improved PSO algorithm integrated with opposition-based learning and tentative perception in networked data centres," *IEEE Access*, vol. 8, pp. 55872–55880, 2020.

[43] C. Wu and R. Buyya, *Cloud Data Centers and Cost Modeling: A Complete Guide to Planning, Designing and Building a Cloud Data Center*. San Mateo, CA, USA: Morgan Kaufmann, 2015.

[44] M. Sharma, K. Arunachalam, and D. Sharma, "Analyzing the data center efficiency by using PUE to make data centers more energy efficient by reducing the electrical consumption and exploring new strategies," *Procedia Comput. Sci.*, vol. 48, pp. 142–148, Jan. 2015.

[45] F. Zhao, G. Nian, H. Jin, L. T. Yang, and Y. Zhu, "A hybrid eBusiness software metrics framework for decision making in cloud computing environment," *IEEE Syst. J.*, vol. 11, no. 2, pp. 1049–1059, Jun. 2017.

[46] M. Dabbagh, B. Hamdaoui, M. Guizani, and A. Rayes, "Energy-efficient resource allocation and provisioning framework for cloud data centers," *IEEE Trans. Netw. Service Manage.*, vol. 12, no. 3, pp. 377–391, Sep. 2015.

[47] TenagaNational. (2020). *Commercial Tariff*. [Online]. Available: https://www.tnb.com.my/commercial-industrial/pricing-tariffs1

[48] B. Tan, H. Ma, and Y. Mei, "A NSGA-II-based approach for service resource allocation in cloud," in *Proc. IEEE Congr. Evol. Comput. (CEC)*, Jun. 2017, pp. 2574–2581.

[49] D. Kliazovich, J. E. Pecero, A. Tchernykh, P. Bouvry, S. U. Khan, and A. Y. Zomaya, "CA-DAG: Modeling communication-aware applications for scheduling in cloud computing," *J. Grid Comput.*, vol. 14, no. 1, pp. 23–39, Mar. 2016.

[50] J. Chase and D. Niyato, "Joint optimization of resource provisioning in cloud computing," *IEEE Trans. Services Comput.*, vol. 10, no. 3, pp. 396–409, May 2017.

[51] J.-M. Pierson, *Large-Scale Distributed Systems and Energy Efficiency: A Holistic View*. Hoboken, NJ, USA: Wiley, 2015.

[52] P. Bertoldi, "The European programme for energy efficiency in data centres: The code of conduct," Joint Res. Center, Eur. Commission, Ispra, Italy, 2012. [Online]. Available: https://scholar.google.com/scholar?q=Bertoldi%20P.%20The%20European%20programme%20for%20energy%20efficiency%20in%20data%20centres:%20the%20code%20of%20conduct.%20European%20Commission%20DG%20JRC%20Institute%20for%20Energy%20document;%20October%202011

[53] M. U. Chowdhury, J. H. Abawajy, A. Kelarev, and H. F. Jelinek, "A clustering-based multi-layer distributed ensemble for neurological diagnostics in cloud services," *IEEE Trans. Cloud Comput.*, vol. 8, no. 2, pp. 473–483, Apr. 2020.

[54] N. J. Kansal and I. Chana, "Cloud load balancing techniques: A step towards green computing," *IJCSI Int. J. Comput. Sci.*, vol. 9, no. 1, pp. 238–246, 2012.

[55] *US Environmental Protection Agency, Greenhouse Gas Equivalencies Calculator*, EPA, Washington, DC, USA, 2013.

[56] Apple Inc. (2014). *Environmental Responsibility Report*. [Online]. Available: https://www.apple.com/environment/reports/docs/apple_environmental_responsibility_report_0714.pdf

[57] A. K. Bashir, Y. Ohsita, and M. Murata, "Abstraction layer based virtual data center architecture for network function chaining," in *Proc. IEEE 36th Int. Conf. Distrib. Comput. Syst. Workshops (ICDCSW)*, Jun. 2016, pp. 31–36.

[58] M. Uddin and A. A. Rahman, "Energy efficiency and low carbon enabler green IT framework for data centers considering green metrics," *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, pp. 4078–4094, Aug. 2012.

[59] M. Uddin and A. A. Rahman, "Techniques to implement in green data centres to achieve energy efficiency and reduce global warming effects," *Int. J. Global Warming*, vol. 3, no. 4, pp. 372–389, 2011.

[60] L. Chiaraviglio, A. Cianfrani, M. Listanti, W. Liu, and M. Polverini, "Lifetime-aware cloud data centers: Models and performance evaluation," *Energies*, vol. 9, no. 6, p. 470, Jun. 2016.

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