Metrics for Sustainable Data Centers

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Abstract—There are a multitude of metrics available to analyze individual key performance indicators of data centers. In order to predict growth or set effective goals, it is important to choose the correct metric and be aware of their expressivity and potential limitations. As cloud based services and the use of ICT infrastructure are growing globally, continuous monitoring and measuring of data center facilities are becoming essential to ensure effective and efficient operations. In this work, we explore the diverse metrics that are currently available to measure numerous data center infrastructure components. We propose a taxonomy of metrics based on core data center dimensions. Based on our observations, we argue for the design of new metrics considering factors such as age, location, and data center typology (e.g., co-location center), thus assisting in the strategic data center design and operations processes.

Index Terms—Data center, metrics/measurements, green computing, energy efficiency, sustainability, taxonomy

1 Introduction

Data centers are structures or groups of structures, dedicated to the centralized accommodation, operation and interconnection of Information and Communications Technology (ICT) equipment providing data storage, processing, and transportation services [1]. The concept of a data center encompasses all of the facilities and infrastructures for power distribution, Heating, Ventilation and Air Conditioning (HVAC) control, together with the necessary levels of resilience and security that are required to provide the desired service availability. Data centers are also one of the most dynamic and critical operations in any business [2].

In recent years, data centers are experiencing a steady growth both in number and in size [3]. These data centers require high availability and reliability for their daily operations, which in turn has an impact on the resources required for operation. The next generation of data centers require solutions that can lower the total cost of ownership and decrease the complexity of management. By applying well defined metrics and making accurate measurements it is possible to better utilize *always-on* data center infrastructure and reduce the recurring cost of Information Technology (IT) and facility management. While the energy consumption of data centers is already significant, the growth of the global cloud-based economy along with society's need for constant social networking connectivity will increase the required resources even further[4]. The world's ICT infrastructure is estimated to consume 1,500 TWh of electricity, roughly 10 percent of global usage. Furthermore, ICT accounts for roughly 2 percent of global carbon emissions with data centers responsible for 14 percent of the total ICT footprint [5]. The operational costs of data centers are vastly different from those of other enterprises as less than 5 percent of the costs are personnel related. Servers are responsible for 45 percent of the amortized costs, followed by infrastructure (25 percent), power draw (15 percent) and networking (15 percent) [6].

Understanding and analyzing data center metrics allows the operators to have a better view on possible inefficiencies by focusing on the core parameters. Metrics also allow architects and operators to measure the performance and effects of changes made to subsystems. A metric is generally defined as *the empirical, objective assignment of numbers, according to a rule derived from a model or theory, to attributes of objects or events with the intent of describing them* [7]. Poorly defined metrics will impede business innovation and prevent meeting environmental sustainability goals.

We present an analysis of metrics that are commonly used in data centers, starting from the power grid and going all the way up to the service delivery. One of the major contributions of this work is the identification of various metrics relating to a data center and classification based on the different core dimensions of data center operations. We define the core dimensions of data center operations as follows: *energy efficiency*, *cooling*, *greenness*, *performance*, *thermal and air management*, *network*, *security*, *storage*, and *financial impact*. To the best of our knowledge there is no such classification available which presents the dimensions of a data center from efficiency to security from the metrics perspective. Furthermore, we derive relationships between metrics, and discuss the advantages and disadvantages of each metric in order to expose the research gaps and illustrate the

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latest research trends in computing the efficiency of a data center. We present a taxonomy of state-of-the-art metrics used in the data center industry which is useful for the researchers and practitioners working on monitoring and improving the energy efficiency of data centers.

The paper is organized as follows: Section 2 presents the related work on metrics for a data center. Section 3 presents a taxonomy of metrics based on different dimensions of a data center, which in turn is useful for designing and operating a sustainable data center. Section 4 discusses open issues and research challenges followed by concluding remarks in Section 5.

2 Related Work

In the last years, significant research efforts and technological developments have been devoted to data centers, targeting energy efficiency and eco-friendliness. The primary step in developing a model to capture the effects of data center management is to decide which dimensions are relevant, define the metrics, and populate them [8]. The Green Grid consortium proposed the Power Usage Effectiveness (PUE) [9], which currently is the prevailing metric. The Green Grid consortium also proposed the Partial Power Usage Effectiveness (pPUE), based on PUE, and the Data Center Infrastructure Efficiency (DCiE) [10] which measures the efficiency of data centers by relating power consumption to IT equipment. PUE and DCiE help data center operators know the efficiency of the data center, where pPUE measures the energy efficiency of a zone in a data center. The consortium also proposed metrics such as Carbon Usage Effectiveness (CUE) [11], Water Usage Effectiveness (WUE) [12], and Electronics Disposal Efficiency (EDE) [13] to measure the CO_2 footprint, the water consumption per year, and the disposal efficiency of the data centers, respectively.

Air flow performance in a data center plays an important role in improving cooling efficiency and space utilization. Metrics to monitor and control the air flow in a data center are discussed in [14], [15]. Munteanu et al. proposed two different metrics based on energy consumption and Central Processing Unit (CPU) usage for calculating useful work done by Internet Data Centers (IDC) [16]. They proposed EnergeTIC Usage Effectiveness (EUE) considering total IDC power, IT power and load levels. They also proposed EUE (CPU), EUE(kWh) and EUE(kWh)-IT. Schaeppi et al. explored energy related metrics for IT equipment, data storage and network equipment [17]. Fiandrino et al. proposed new metrics for computing energy efficiency of the data center communication systems, processes and protocols which includes communication network energy efficiency, network power usage effectiveness and network performance related metrics [18].

The European Union financed an eight-project cluster of over 50 partners to develop new environmental efficiency metrics and methodologies. The projects are All4Green, CoolEmAll, GreenDataNet, RenewIT, GENiC, GEYSER, Dolfin and DC4Cities. The cluster has published several works in which they analyze existing metrics and also propose novel metrics to assess the performance of data centers [19], [20]. Capozzoli et al. reviewed thermal, power and energy consumption metrics [21]. Aravanis et al. introduced new metrics for the assessment of flexibility and sustainability of data centers [22]. In [23], Siso et al. propose and evaluate several metrics for the CoolEmAll project.

Daim et al. explored measurable components of a data center and proposed a new metric that fills the gap in measuring the data center equipment power and uses a credit-based system for data centers not meeting the standard [8]. Chen et al. identified and presented usage-centric green performance indicators at various levels such as server and storage [24]. Wang et al. presented a set of performance metrics for a green data center [25]. They focused on available benchmarks and on how performance metrics can be used to measure the greenness.

Wiboonrat discussed the effect of a data center outage and provided a solution to minimize the data center downtime [26]. The author proposed improvements on the data center topologies to reduce the failure rate. The American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) provides a common set of environmental guidelines for data processing environments, equipment and guidance on server metrics which enables data center operators to develop their own envelop that matches their business values [27], [28].

The Tier classification, as defined by the Uptime Institute, gives the data center industry a consistent mechanism for comparing typical facilities based on their up-time and facility performance [29]. Furthermore, Tier classification enables companies to align their infrastructure investment with business goals specific to their growth and technology strategies. The Tier classification distinguishes between the following tiers:

- Tier I: a facility composed of a single path for power and cooling distribution. It does not contain redundant components and provides 99.671 percent availability.
- Tier II: a facility composed of a single path for power and cooling distribution, it contains redundant components and provides 99.741 percent availability.
- Tier III: a facility composed of multiple active power and cooling distribution paths, and redundant components with only one active path. It is concurrently maintainable and provides 99.982 percent availability.
- Tier IV: facility composes of all components of Tier III and it is fault tolerant, it provides 99.995 percent availability.

3 A Taxonomy of Data Center Metrics

Measuring how resources are used in a data center is crucial to understand the overall efficiency, reduce the costs of operations and achieve sustainability goals. Organizations are continuously searching for information and insights that offer control over their data centers. To remain competitive with their peers in the industry, they must ensure optimal utilization of resources in order to increase efficiency while minimizing environmental impact. This is only possible if there is information available that is meaningful and actionable. Well-defined and organized metrics increase the organization's productivity and assist with making management decisions.

For efficient and eco-friendly operation of data centers, we need to monitor all the components of a data center.

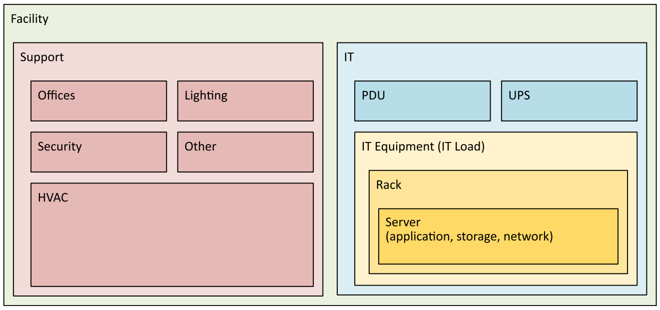

Fig. 1. Division in categories for data centers.

These components are visualized in Fig. 1. At the top level, we have the entire facility, which encompasses energy and other resources going into IT related components, and into support components such as lighting, HVAC, and offices. The IT power flows to the Power Distribution System (PDS) and Uninterruptible Power Supply (UPS), which further distributes the power to IT equipment. The IT equipment consists of servers that are organized into racks. Servers can include application servers, networking equipment such as switches, routers, and storage servers. This classification enables us to assign a category to each metric and group them based on these categories.

The following dimensions emerge as core dimensions: Energy Efficiency, Cooling, Greenness, Performance, Thermal and Air management, Network, Storage, Security, and Financial Impact. Many different metrics exist, each with it's own approach to measuring performance of a data center, each with its own advantages, drawbacks and limitations. We provide a survey of data center metrics, and for each metric describe the unit in which it is expressed, the objective, the optimal value as well as the scale at which the metric operates. The objective specifies the optimization that should be done for a given metric (ex: minimize, maximize). The optimal value is the ideal or target value for the metric. Furthermore, there are inter-dependencies between individual metrics, as some are based on or have a strong relationship with other metrics. The relationships between metrics can be defined as 'uses'-relationship and 'based on'-relationship. The 'uses'-relationship exists when a metric uses another metric directly as input for the calculation. The 'based on'-relationship indicates that a metric is based on the principles of another metric.

3.1 Energy Efficiency Metrics

The energy efficiency of a system is defined as the ratio of useful work done by a system to the total energy delivered to the system. For data centers, the energy efficiency translates into the useful work performed by different subsystems. An overview of available energy efficiency metrics is presented in Table 1. The unit of each metric is listed, including the objective, optimal value and the category to

TABLE 1
Energy Efficiency Metrics Overview

Acronym	Full Name	Unit	Objective	Optimal	Category	Ref.
APC	Adaptability Power Curve	Ratio	Maximize	1.0	Facility	[22]
CADE	Corporate Average Data Center Efficiency	Percentage	Maximize	1.0	Facility	[30]
CPE	Compute Power Efficiency	Percentage	Maximize	1.0	Facility	[31]
DCA	DCAdapt	Ratio	Minimize	$-\infty$	Facility	[22]
DCcE	Data Center Compute Efficiency	Percentage	Maximize	1.0	Server	[32]
DCeP	Data Center Energy Productivity	UW/kWh	Maximize	∞	Facility	[33]
DCiE	Data Center Infrastructure Efficiency	Percentage	Maximize	1.0	Facility	[10]
DCLD	Data Center Lighting Density	kW/ft^2	Minimize	0.0	Facility	[34]
DCPD	Data Center Power Density	kW/Rack	Maximize	∞	Rack	[34]
DCPE	Data Center Performance Efficiency	UW/Power	Maximize	∞	Facility	[35]
DC-FVER	Data Center Fixed to Variable Energy Ratio	Ratio	Minimize	1.0	Facility	[36]
DH-UE	Deployed Hardware Utilization Efficiency	Percentage	Maximize	1.0	Server	[37]
DH-UR	Deployed Hardware Utilization Ratio	Percentage	Maximize	1.0	Server	[37]
DPPE	Data Center Performance Per Energy	Ratio	Maximize	1.0	Facility	[38]
DWPE	Data center Workload Power Efficiency	Perf/Watt	Maximize	∞	Server	[39]
EES	Energy ExpenseS	Ratio	Maximize	1.0	Facility	[22]
EWR	Energy Wasted Ratio	Ratio	Minimize	0.0	Facility	[38]
GEC	Green Energy Coefficient	Percentage	Maximize	1.0	Facility	[38]
H-POM	IT Hardware Power Overhead Multiplier	Ratio	Minimize	1.0	IT Equipment	[37]
ITEE	IT Equipment Energy	Cap/kW	Maximize	∞	IT Equipment	[38]
ITEU	IT Equipment Utilization	Percentage	Maximize	1.0	IT Equipment	[38]
OSWE	Operating System Workload Efficiency	OS/kW	Maximize	∞	Facility	[40]
PDE	Power Density Efficiency	Percentage	Maximize	1.0	Rack	[41]
PEsavings	Primary Energy Savings	Ratio	Maximize	1.0	Facility	[22]
PUE_{1-4}	Power Usage Effectiveness Level 1-4	Ratio	Minimize	1.0	Facility	[10], [19]
$PUE_{scalability}$	Power Usage Effectiveness Scalability	Percentage	Maximize	1.0	Facility	[42]
pPUE	Partial Power Usage Effectiveness	Ratio	Minimize	1.0	Facility	[10]
PpW	Performance per Watt	Perf/Watt	Maximize	∞	Server	[43]
ScE	Server Compute Efficiency	Percentage	Maximize	1.0	Server	[32]
SI-POM	Site Infrastructure Power Overhead Multiplier	Ratio	Minimize	1.0	Facility	[37]
SPUE	Server Power Usage Efficiency	Ratio	Minimize	1.0	Facility	[39]
SWaP	Space, Watts and Performance	Ratio	Maximize	∞	Rack	[44]
TUE	Total-Power Usage Effectiveness	Ratio	Minimize	1.0	Facility	[45]

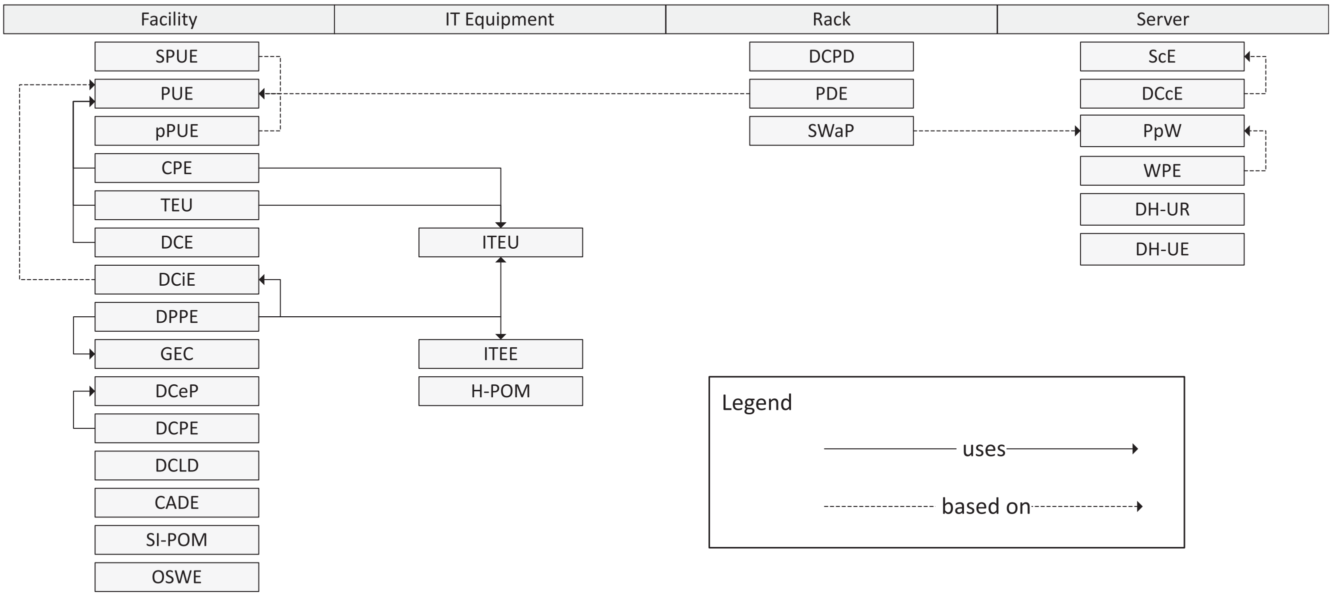

Fig. 2. Relationships between energy efficiency metrics.

which it belongs. We analyze the relationships between these metrics and present them in Fig. 2. In Fig. 2, we organize the metrics horizontally based on their category and visualize the relationships that exist among them. The most popular energy efficiency metric, PUE, is used by a large number of other metrics either directly or as a derivation, as highlighted in Fig. 2. For example, Server Power Usage Efficiency (SPUE) and pPUE metrics are based on the same principles as the PUE metric. The Data Center Performance Per Energy (DPPE) metric is also noteworthy as the metric is a combination of four other metrics: DCiE, Green Energy Coefficient (GEC), IT Equipment Energy (ITEE), and IT Equipment Utilization (ITEU). Details and definitions of these metrics are given in Appendix A, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TSUSC.2017.2701883. To calculate the ITEU, one needs to know the exact power used by fans, voltage regulators and other components inside IT equipment. It is not clear how to measure the total energy that goes into IT equipment accurately. Defining coefficients for different types of IT equipment is also challenging especially in the heterogeneous environments of co-location data centers. To accurately calculate the Operating System Workload Efficiency (OSWE) metric, the number of operating systems needs to be known, including operating systems of virtual machines. We can conclude that some of these metrics require accurate and very hardware-specific data in order to be useful.

3.2 Cooling Metrics

The heat generated by the IT equipment in a data center must be controlled to maintain high levels of operational performance. Therefore, cooling plays a vital role in any data center. The complex interconnection of HVAC systems ensures optimal conditions for the computing environment in a data center, guaranteeing the life span, scalability and flexibility of the servers [52]. An overview of the available cooling metrics that can be applied in the context of data centers can be found in Table 2. Details and definitions of these metrics are given in Appendix B, available in the online supplemental material.

3.3 Green Metrics

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 data center is a system in which the mechanical, lighting, electrical and IT equipment are designed for maximum energy efficiency and minimum environmental impact" [58], [59]. Green IT benefits the environment by improving energy efficiency, lowering

TABLE 2
Cooling Metrics

Acronym	Full Name	Unit	Objective	Optimal	Category	Ref.
AEUF	Air Economizer Utilization Factor	Percentage	Maximize	1.0	HVAC	[46]
CoP	Coefficient of Performance Ensemble	Ratio	Maximize	∞	Facility	[47]
DCCSE	Data Center Cooling System Efficiency	kW/ton	Minimize	0.0	HVAC	[48]
DCSSF	Data center Cooling System Sizing Factor	Ratio	Minimize	1.0	HVAC	[48]
EER	Energy Efficiency Ratio	Ratio	Maximize	∞	Facility	[19]
HSE	HVAC System Effectiveness	Ratio	Maximize	3.5	HVAC	[49]
RI	Recirculation Index	Ratio	N/A	N/A	HVAC	[50]
WEUF	Water Economizer Utilization Factor	Percentage	Maximize	1.0	HVAC	[51]

TABLE 3
Green Metrics

Acronym	Full Name	Unit	Objective	Optimal	Category	Ref.
-	CO_2 Savings	Ratio	Maximize	1.0	Facility	[22]
CUE	Carbon Usage Effectiveness	$KgCO_2$/kWh	Minimize	0.0	Facility	[11]
EDE	Electronics Disposal Efficiency	Percentage	Maximize	1.0	Facility	[13]
ERE	Energy Reuse Effectiveness	Percentage	Minimize	0.0	Facility	[53]
ERF	Energy Reuse Factor	Percentage	Maximize	1.0	Facility	[53]
GEC	Green Energy Coefficient	Percentage	Maximize	1.0	Facility	[38]
GUF	Grid Utilization Factor	Percentage	Minimize	0.0	Facility	[22]
MRR	Material Recycling Ratio	Percentage	Maximize	1.0	Facility	[54]
Omega	Water Usage Energy / ω	Ratio	Minimize	0.0	Facility	[55]
TCE	Technology Carbon Efficiency	Pounds of CO_2/kWh	Minimize	0.0	Facility	[56]
TGI	The Green Index	Ratio	N/A	N/A	Facility	[57]
WUE	Water Usage Effectiveness	Liters/kWh	Minimize	0.0	Facility	[12]

greenhouse gas emissions, using renewable resources, and by encouraging reuse and recycling [60]. Table 3 presents various green metrics which reflect the greenness of the data center in terms of carbon footprint, heat reuse, efficiency of water consumption and use of renewable energy resources. Fig. 3 illustrates the relationships between these metrics using the following concepts: *Reduce* (reducing resources), *Reuse* (reusing resources), *Recycle* (recycling resources) and *Renewable* (use of renewable resources). We organize the green metrics horizontally according to the these four concepts and vertically based on the category in which they operate, as illustrated in Fig. 3. Details and definitions of these metrics are given in Appendix C, available in the online supplemental material.

3.4 Performance Metrics

The performance of a data center is the total effectiveness of the system, including throughput, response time, and availability [25]. Measuring performance and productivity is crucial as sub-optimal performance has operational and financial implications for a data center. When determining the performance of a data center one can encounter several difficulties including: distinguishing significant workloads, overhead of performance measurements, energy distribution losses, and measuring the energy consumption at various levels of the data center. Measuring the actual performance and productivity allows data center operators to determine how to further improve the performance and plan for future work loads. An overview of the metrics which measure the performance of various components in data centers is presented in Table 4. Details and definitions of these metrics are given in Appendix D, available in the online supplemental material.

3.5 Thermal and Air Management Metrics

Thermal and air management metrics measure environmental conditions of the data center and also determine how air flows within a data center, from cooling units to the vents. These metrics assist with the diagnostic analysis to determine, for example, the amount of re-circulation by-pass air. In general, these metrics are based on the relationship between air flow rate and ambient temperature. The metrics can be influenced by internal parameters and location [2]. Metrics like temperature, humidity, dew point and heat flux are used to prevent the over-heating, maintain the humidity levels, capture the current condition of the cooling system and to assist with making the correct decisions. The dimension, objective, optimal value of the outcomes, and the scale at which these metrics operate are presented in Table 5. Details and definitions of these metrics are given in Appendix E, available in the online supplemental material.

Air management metrics address air flow efficiency and separation of hot and cold air streams. We observed that most of the air management metrics depend on common inputs. We have analyzed these metrics, looking specifically at the

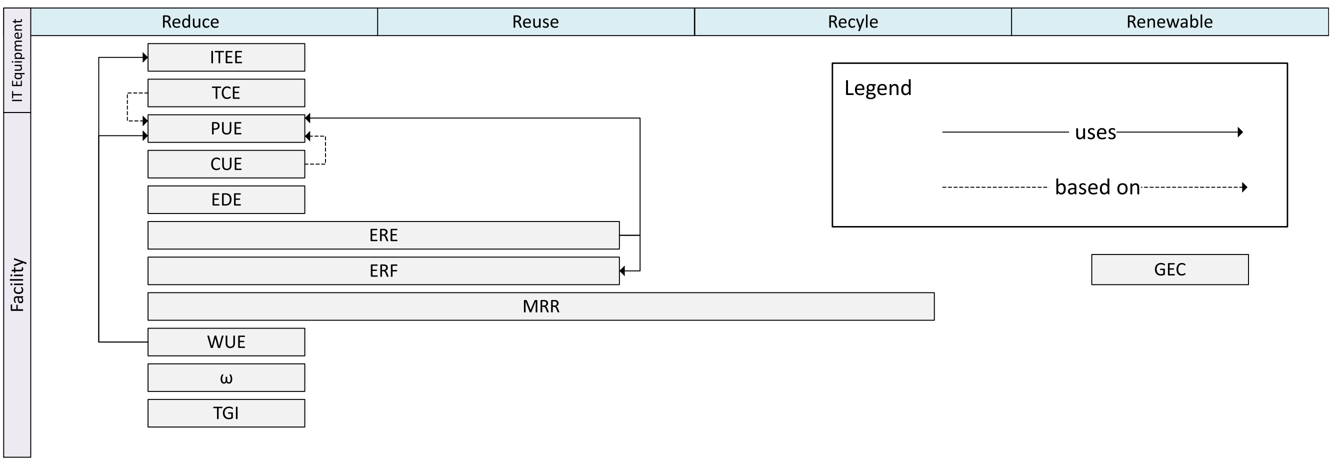

Fig. 3. Relationship between green metrics.

TABLE 4
Performance Metrics

Acronym	Full Name	Unit	Objective	Optimal	Category	Ref.
ACE	Availability, Capacity, and Efficiency Performance Score	Ratio	Maximize	1.0	HVAC	[61]
CPU	Central Processing Unit Usage	Percentage	Maximize	1.0	Server	[62]
DCP	Data Center Productivity	Useful work/Watt	Maximize	∞	Facility	[63]
DEEPI	Data Center Energy Efficiency and Productivity Index	Prod./Watt	Maximize	∞	Facility	[64]
DR	Dynamic Range	Ratio	Maximize	1.0	Server	[65]
EP	Energy Proportionality	Ratio	Maximize	1.0	Server	[66]
FpW	Flops per Watt	Float. ops/Joule	Maximize	∞	Server	[62]
IPR	Idle-to-peak Power Ratio	Ratio	Minimize	0.0	Server	[67]
LD	Linear Deviation	Ratio	Minimize	0.0	Server	[65]
LDR	Linear Deviation Ratio	Ratio	Minimize	0.0	Server	[67]
PG	Proportionality Gap	Ratio	Minimize	0.0	Server	[65]
SWaP	Space, Watts and Performance	Ratio	Maximize	∞	Facility	[68]
U_{DC}	Data Center Utilization	Percentage	Maximize	1.0	Facility	[69]
U_{server}	Server Utilization	Percentage	Maximize	1.0	Server	[69]
UCF	Uninterruptible Power Supply Crest Factor	Ratio	Optimize	1.4	UPS	[70]
UPEE	Uninterruptible Power Supply Energy Efficiency	Percentage	Maximize	1.0	UPS	[72]
UPF	Uninterruptible Power Supply Power Factor	Ratio	Maximize	1.0	UPS	[70]
UPFC	Uninterruptible Power Supply Power Factor Corrected	Ratio	Maximize	1.0	UPS	[71]
USF	Uninterruptible Power Supply Surge Factor	Ratio	Optimize	1.5	UPS	[70]

inputs, airflow path, and purpose of each metric. The result of this analyses can be seen in Fig. 4. Return Heat Index (RHI) and Supply Heat Index (SHI) differ in airflow paths. Balance Ratio (BR) can be developed as a function of Recirculation Ration (RR) and Bypass Ratio (BPR).

3.6 Network Metrics

The data center network acts as a core component for providing numerous services. Networking equipment is responsible for up to 15 percent of a data center's amortized cost [6]. To increase the efficiency of data centers, operators should improve the energy efficiency of the network of data centers. The performance variability in the network harms the application performance and causes the revenue loss. A data center's network performance can typically be characterized using well-known metrics such as bandwidth, Network Power Usage Effectiveness (NPUE), Communication Network Energy Efficiency (CNEE), reliability and throughput [81]. An overview of the network metrics with the unit of each metric, objective, optimal value and the scale at which these metrics operate are presented in Table 6. Details and definitions of these metrics are given in Appendix F, available in the online supplemental material.

3.7 Storage Metrics

Productive and efficient storage execution for cloud data centers can be troublesome as it requires interaction with many components in the infrastructure such as application servers, storage devices, and network equipment. By applying a set of metrics for storage operations in the data centers the storage performance can be increased by continuous monitoring of these metrics [88]. Overall Storage Efficiency (OSE) and slot utilization, for example, provide for better visibility into how efficiently storage capacity is being utilized. Traditional metrics are unable to capture the improved efficiency achieved using new tools and methods

TABLE 5
Thermal and Air Management Metrics

Acronym	Full Name	Unit	Objective	Optimal	Category	Ref.
-	Airflow Efficiency	W/cfm	Minimize	0.0	Facility	[48]
BPR	Bypass Ratio	Ratio	N/A	N/A	Facility	[15]
BR	Balance Ratio	Ratio	N/A	N/A	Facility	[15]
CI	Capture Index	Percentage	Maximize	1.0	HVAC	[73]
DC	Data Center Temperature	^oC or ^oF	Optimize	18 - 27^{oC}	Facility	[27]
DP	Dew Point	^oC or ^oF	Optimize	17^{oC}	Facility	[27]
HF	Heat Flux	W/m^2	Minimize	0.0	Facility	[27]
IoT	Imbalance of Temperature	Percentage	Minimize	0.0	Rack-Server	[19]
-	Mahalanobis Generalized Distance (D^2)	Unit	Minimize	0.0	Facility	[74]
M	Mass Flow M_c, M_n, M_{bp}, M_r, M_s	cfm	N/A	N/A	Facility	[75]
RCI	Rack Cooling Index	Percentage	Maximize	1.0	Rack	[76]
-	Relative Humidity	Percentage	Optimize	60%	Facility	[77]
RHI	Return Heat Index	Ratio	Maximize	1.0	Facility	[78]
RR	Recirculation Ratio	Ratio	N/A	N/A	Facility	[15]
RTI	Return Temperature Index	Percentage	Optimize	1.0	Rack	[79]
SHI	Supply Heat Index	Ratio	Maximize	1.0	Facility	[78]
-	β-index	Ratio	N/A	N/A	Rack	[80]

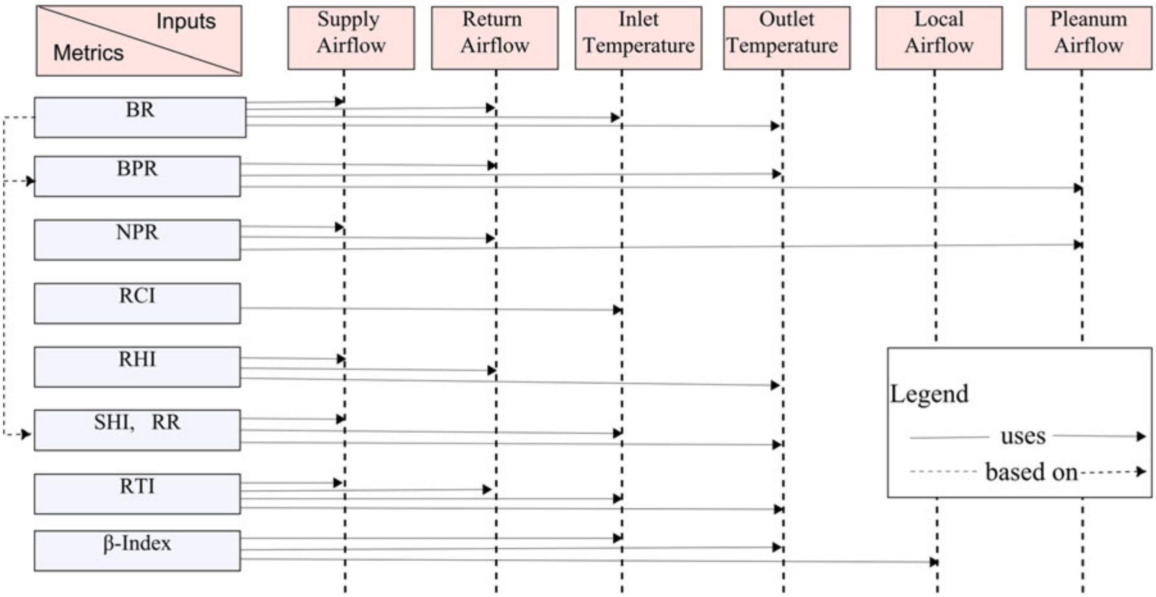

Fig. 4. Relationship between thermal and air management metrics.

TABLE 6
Network Metrics

Acronym	Metric	Unit	Objective	Optimal	Category	Reference
BJC	Bits per Joule Capacity	bits/joule	Maximize	∞	IT Equipment	[82]
CNEE	Communication Network Energy Efficiency	Joule/bit	Minimize	0.0	IT Equipment	[18]
DS	Diameter Stretch	Ratio	Optimize	1.0	IT Equipment	[83]
ECR-VL	Energy Consumption Rating Variable Load	Watts/Gbps	Minimize	0.0	IT Equipment	[84]
NPUE	Network Power Usage Effectiveness	Ratio	Minimize	1.0	IT Equipment	[18]
-	Network Traffic per Kilowatt-Hour	Bits/kWh	Maximize	∞	Facility	[85]
PS	Path Stretch	Ratio	Optimize	1.0	IT Equipment	[83]
RS_{max}	Maximum Relative Size	Ratio	Maximize	1.0	IT Equipment	[83]
TEER	Telecommunications Energy Efficiency Ratio	Ratio	Maximize	∞	IT Equipment	[86]
$U_{network}$	Network Utilization	Percentage	Maximize	1.0	IT Equipment	[69]

TABLE 7
Storage Metrics

Acronym	Metric	Unit	Objective	Optimal	Category	Reference
-	Capacity	GB/Watt	Maximize	∞	Storage	[87]
LSP	Low-cost Storage Percentage	Percentage	Maximize	1.0	Storage	[88]
-	Memory Usage	Ratio	Maximize	1.0	Storage	[89]
OSE	Overall Storage Efficiency	Ratio	Maximize	1.0	Storage	[88]
RT	Response Time	Milliseconds	Minimize	0.0	Storage	[87]
SU	Slot Utilization	Percentage	Maximize	1.0	Storage	[87]
-	Throughput	Bytes/second	Maximize	∞	Storage	[89]
$U_{storage}$	Storage Usage	Percentage	Maximize	1.0	Storage	[69]

such as trim storage and just-in-time allocations. We perceive the requirement for a single set of metrics that reflects storage utilization across a changing technology base. We analyze and present the storage metrics along with their units as well as the objective, optimal value of the outcomes and the scale at which these metrics operate in Table 7. Details and definitions of these metrics are given in Appendix G, available in the online supplemental material.

3.8 Security Metrics

Security metrics quantify how well security strategies are deployed. "A security metric is a system of related dimensions (compared against a standard) enabling quantification of the degree of freedom from the possibility of suffering damage or loss from malicious attacks" [95]. The basic security goals in a data center include authentication, authorization, and data protection.

A data center is designed to withstand everything from corporate espionage to terrorists, to natural disasters. To ensure high security standards, data centers need to follow several practices and guidelines. Data centers should be built on the right site with walls capable of withstanding explosions. To handle fire break outs, data centers should establish fire compartments and monitor the environment with the

TABLE 8
Security Metrics

Acronym	Metric	Unit	Objective	Optimal	Category	Reference
ACPR	Average Comparisons Per Rule	Count	Minimize	0.0	IT Equipment	[90]
AS	Accessibility Surface	Count	Optimize	-	IT Equipment	[90]
ATR	Application Transaction Rate	Bits/sec	Maximize	∞	IT Equipment	[91]
CC	Concurrent Connections	Count	Maximize	∞	IT Equipment	[90]
CER	Connection Establishment Rate	Connections/sec	Maximize	∞	IT Equipment	[92]
CTR	Connection Tear down Rate	Connections/sec	Optimize	-	IT Equipment	[92]
DeD	Defense Depth	Count	Maximize	∞	Facility	[91]
DeP	Detection Performance	-	Maximize	1.0	IT Equipment	[93]
DTE	Data Transmission Exposure	Count	Minimize	0.0	IT Equipment	[93]
FC	Firewall Complexity	Ratio	Optimize	-	IT Equipment	[90]
-	HTTP Transfer Rate	Bits/sec	Maximize	0.0	IT Equipment	[92]
IAS	Interface Accessibility Surface	Count	Optimize	-	IT Equipment	[90]
IPFH	IP Fragmentation Handling	-	Maximize	∞	IT Equipment	[92]
-	IP throughput	Bits/sec	Maximize	∞	IT Equipment	[94]
ITH	Illegal Traffic Handling	Percentage	Maximize	∞	IT Equipment	[92]
-	Latency	Milli-seconds	Minimize	0.0	IT Equipment	[91]
RA	Rule Area	Count	Optimize	-	IT Equipment	[90]
RC	Reachability Count	Count	Minimize	0.0	Facility	[93]
RCD	Rogue Change Days	Days	Minimize	0.0	IT Equipment	[93]
T	Vulnerability Exposure	days	Minimize	0.0	IT Equipment	[93]

help of aspirating smoke detectors. Data centers should have redundant utilities, a buffer zone around the site, a limited number of entry points, plenty of surveillance cameras, etc. In addition, data center employees, customers and visitors should be authenticated at least three times [96].

Most of the data centers have layered security in place. The number of layers of security increases with the tier of the data centers with Tier 4 data centers having more than 6 security levels [97], [98]. Layered security include perimeter fence equipped with senors, badge access to inner doors, a guard escorting visitors, a floor to ceiling turnstile, access card or bio-metric authentication to secure parts of the data center, video surveillance, and locked cages for servers. Some data centers use testing, development and production zones, where production zones have high security and testing zones have less [99]. Testing zones are used for research activities and the production zone will have systems that are running operations of the customers.

For full control, it is advised to have security zones in a data center networks to provide better visibility and improve detection performance [100]. A security zone is created in a network, consisting of a group of IT equipment that have similar access control requirements. Security zones are logical entities that provide isolation and minimize security risks. They are organized as layered trust zones with inner layers having higher levels of security than the outer ones. This layering offers one way communication from higher trust zones to lower trust zones. Furthermore, virtual private networks can be used to manage and protect the environment. In a virtualized environment, strict enforcement of security policies may not be possible due to migrations of, for example, virtual machines across data centers [101]. Providers and customers should communicate their expectations for security as part of agreement process and component level security controls need to be developed in the shared control model. Table 8 lists the metrics for complexity and performance of firewalls, intrusion detection and prevention systems. Details and definitions of these metrics are given in Appendix H, available in the online supplemental material.

3.9 Financial Impact Metrics

Most of the organizations depend on non-financial, operational metrics except in setting up budgets and measuring the projects [104]. Employing financial metrics in a balanced score-card will help the operators put other key metrics such as outage reports and service quality metrics in a financial perspective.

An example of such a metric is Total Cost of Ownership (TCO), which is the main cost driver for IT and represents a significant expense for other units such as cooling and lighting. The metric empowers us to settle on better venture choices and manage demand. Capital expenditure and Operational expenditure indicate the amount of funds required to purchase the physical assets and the cost incurred for making them operational, respectively. Along with other metrics, such as carbon credit and Return On Investment, these assist in the development of an effective business case for data center modernization. An overview of the financial impact metrics is presented in Table 9 where the unit of each metric is listed including the objective, optimal value, and the category to which it belongs. Definition and detailed description of these metrics are given in Appendix I, available in the online supplemental material.

We analyze the relationships between these metrics and present them in Fig. 5. It shows that the Total Cost of Ownership (TCO), is calculated as a sum of Capital Expenditure (CapEx) and Operational Expenditure (OpEx) of the data center. Component failure rate (λ) and component repair rate (μ) are calculated using Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) respectively.

4 Open Issues and Research Challenges

There are a multitude of metrics to measure and monitor different aspects of data centers. When looking at the relationship between the metrics and challenges associated with

TABLE 9
Financial Impact Metrics

Acronym	Metric	Unit	Objective	Optimal	Category	Reference
A	Availability	Ratio	Maximize	1.0	Facility	[102]
BVCI	Business Value of Converged Infrastructure	Dollars	Maximize	∞	Facility	[103]
CapEx	Capital Expenditure	Dollars	NA	NA	Facility	[104]
CCr	Carbon Credit	Tons of Carbon	Maximize	∞	Facility	[87]
MTBF	Mean Time Between Failures	Hours	Maximize	∞	Facility	[105]
MTTF	Mean Time To Failure	Hours	Maximize	∞	Storage	[102]
MTTR	Mean Time To Repair	Hours	Minimize	0.0	Facility	[102]
OpEx	Operational Expenditure	Dollars	Minimize	0.0	Facility	[104]
ROI	Return On Investment	Ratio	Maximize	∞	Facility	[106]
TCO	Total Cost of Ownership	Dollars	NA	NA	Facility	[107]
λ	Reliability	Faults/Hour	Minimize	0.0	Facility	[102]

using them, it becomes apparent that there is no single metric which covers all dimensions of the data center's performance. Even per dimension, there are several metrics promising to provide insight into the same area, through similar or different methods. However, none of the metrics are designed for comparing data centers amongst each other. Although the PUE metric is currently used for this purpose, it was never intended to be used as a comparison metric [9]. Instead the metric was envisioned to be an internal measurement to steer the data center towards higher levels of efficiency, by knowing which areas have a low efficiency in terms of energy consumption. For example, the IT load of a data center influences the PUE significantly. Furthermore, the PUE is also influenced by the weather and the location of the data center. Therefore, comparisons between data centers using PUE are most often not representative of the actual situation.

It is not possible for a single metric to represent the energy efficiency for all of the possible combinations of an IT environment. The Corporate Average Data Center Efficiency (CADE) metric can be extended by considering how efficiently servers, storage, and network equipment are utilized. Data Center Infrastructure Efficiency (DCiE) metric is effective at discovering the initial problem and helps justify the need to implement energy saving changes. However, the DCiE metric varies for each data center as it depends on the IT electrical load, which is a variable and site specific function of the IT software, architecture, hardware, load and efficiency. Due to this variability, we can not predict the impact of changes to the data center using DCiE. The Green Index (TGI) metric allows for flexibility in green benchmarking as it can be used and viewed in different ways by its end users. Even though we have specified the performance-per-watt metric for computing TGI, it can be computed with any other energy-efficient metric. TGI does not consider the power consumed outside of the IT equipment context. Therefore it can be extended by including components such as the cooling infrastructure.

Overhead metrics such as IT Hardware Power Overhead Multiplier (H-POM), Site Infrastructure Power Overhead Multiplier (SI-POM) give an understanding of a data center's energy use considering variations in IT equipment energy and the committed power to a facility. These metrics provide useful insights to the operators where modular provisioning is used. Because of the complexity and the unpredictable nature of data centers, a credible quantitative measure of security risk is not currently feasible. Security managers should chose a set of metrics which allows for better decision making and actual security improvements. The specific metrics discussed in this work can be refined and expanded to reduce the risk of a successful cyber-attack. The study of the given metrics has identified the need for improved measurement tools.

The number of inter-dependencies between different metrics on the facility level is large. It is important to be aware of these relationships, as metrics can have certain limitations that affect other metrics associated with them. When combining existing metrics into new ones, or basing new metrics on existing ones, the flaws of the existing metrics are usually not overcome, and sometimes even increased. Therefore, it is useful to understand these shortcomings and know what a metric can and cannot measure. Applying metrics is even more difficult for co-location data centers as the equipment, space and bandwidth are available for rental in these types of data centers.

Furthermore, there is a need for a metric which is designed with comparison in mind from its inception. Ideally, this metric should attempt to normalize the data in such a way that a fair comparison between data centers can be performed. The metric should take into account the utilization of data centers, as well as the location and weather. A metric which is highly dependent on those factors is PUE: a change in the utilization efficiency of the data center is immediately reflected in the value variations of the PUE. The location of the data center also has an influence on the outcome of this metric, as does the weather.

By applying a well-defined set of metrics which measure energy consumption and environmental impact during data center operation, and while making choices at various levels, it is possible for data centers to be planned, designed, implemented and operated in an energy-aware and more eco-friendly manner. We present a summary of the metrics including the dimensions along with their use and issues in Table 10. We make a distinction between absolute and

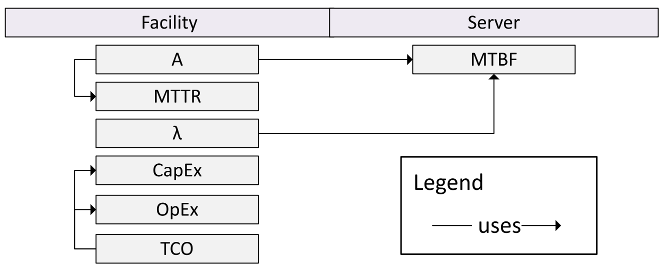

Fig. 5. Relationship between financial metrics.

TABLE 10
Data Center Metrics Use, Issues, and Challenges

Dimension	Use	Absolute Metrics	Relative Metrics	Issues and Challenges
Energy Efficiency	These metrics are a series of indicators relevant to quantitative measure of energy efficiency of data center and its components. Some metrics are used to know how efficiently a data center transfers power from the source to the IT equipment and some metrics define IT load versus overhead.	APC, CADE, DCA, DCeP, DCLD, DCPD, DC-FVER, DH-UE, DH-UR, EES, EWR, GEC, H-POM, ITEE, OSWE, PEsavings, PUE, PUE, PpW, ScE, SI-POM, TUE.	CPE, DCcE, DCiE, DCPE, DPPE, DWPE, PDE, pPUE, SPUE, SWaP.	Energy consumption data disaggregated by data center sub-components may not be available. It is hard to know the number of operating systems and virtual machines running in a data center.
Cooling	These metrics characterize the efficiency of the HVAC systems and how well these serve the cooling demand.	AEUF, COP, DCCSE, DCSSF, EER RI, WEUF.	HSE.	It is challenging to determine whether there is adequate under–floor cooling in a consistently advancing environment, where heat densities change within rack and one rack to the next. Data center cooling system must balance ambient environment with supplemental cooling to optimize efficiency.
Greenness	These metrics explain the carbon foot- print of the data centers and IT equipment. Also, we can assess how much green energy used, how much energy is exported for reuse and how efficiently a data center is using water.	CO_2 Savings, EDE, ERF, GUC, MRR, TGI.	CUE, ERE, GEC, TCE, WUE, ω.	Some of these metrics requires seasonal benchmarking to capture region and season changes.
Performance	These metrics measure the productivity of data center, effectiveness in delivering service and agility in responding dynamically to change.	CPU Usage, DCP, DR, EP, FpW, LD, LDR, PG, UCF, UPF, USF, U_{DC}, U_{server}, UPS Energy Efficiency.	ACE, DEEPI, SWaP.	”useful computing work” is not defined uniquely. Correct base scores may be challenging without the right tools.
Thermal & Air Mana–gement	These metrics help us to take care of efficient air flow, temperature issues and aisle pressure management.	Airflow efficiency, CI, DC, DP, HF, IoT, D^2, Mass Flow, RCI, Relative Humidity, RHI, RR, RTI, SHI, β-Index.	BPR, BR, NPR, RR.	It is difficult to make proper aisle arrangement. For efficient airflow, we must address bypass & re-circulation air flow.
Network	These metrics give the data center network energy efficiency, utilization and traffic demands.	BJC, CNEE, ECR-VL, Network Traffic per Kilowatt-Hour, RS_{max}, TEER, $U_{network}$.	DS, NPUE, PS.	Measuring variable energy vary from one to other operator. Useful work is not defined properly.
Storage	Using these metrics storage operations and performance can be monitored. We get better visibility into how proficiently our capacity is being utilized to store client information	Capacity, Memory Usage, OSE, RT, SU, Throughput, $U_{storage}$.	LSP.	Measuring customer stored data and its criticality is difficult due to data duplication and the users view differ from the storage frame view.
Security	These metrics are useful for protecting servers from attacks and continuously monitor physical and virtual servers and clouds. Further these metrics cover some basic measurements of firewall performance in a data center.	ACPR, ATR, CC, CER, CTR, DeD, DeP, DTE, FC, HTTP Transfer Rate, IP Throughput, Latency, RA, RC, RCD, T	AS, IAS, IPFH, ITH.	These metrics are highly dependent on internal governance, compliance standards and SLA.
Financial Impact	These metrics calculate total cost of ownership, financial impact of data center outages, return on investments on management tools and technologies for sustainable data center.	BVCI, CapEx, MTBF, MTTF, MTTR, OpEx, ROI.	A, CCr, TCO, λ.	Confidentiality concerns associated with revealing costs for a particular facility. Carbon Credit may vary based on the country policies.

relative metrics. Absolute metrics do not depend on other metrics where as relative metrics do depend on other ones [108].

Energy efficiency metrics measure the computing and non-computing energy used in a data center. These metrics measure the efficiency at various levels of granularity starting from operating system to data center. But it is difficult to measure the energy consumption at operating system level. Also, it is challenging to measure the energy consumption at sub-component level of a data center, as these low level measurements are often not available.

Cooling metrics are used to specify the performance of the Computer Room Air Conditioning (CRAC)/Heating, Ventilation and Air Conditioning (HVAC) units and proper sizing of the cooling units. These metrics also measure the efficiency of the cooling systems. Estimating power and cooling capacity requirements using the ratings found on nameplates of IT equipment may not be accurate. Another issue is that heat densities change within racks, and also differ from one rack to the next.

Green metrics measure the environmental impact of a data center and its components. They highlight the importance of green energy and measure the efficiency of recycling and reuse in a data center. Efficient measurement of these metrics require capturing regional and seasonal changes to enable comparison of different data centers.

A data center can increase its productivity by clearly defining performance metrics. These metrics help to measure IT performance and productivity of the data center and also identify problem areas. Metrics can range from low level UPS performance to high level data center utilization. Across all the components, a single fault may affect many other systems and ultimately decrease the overall performance of the data center. Operators rely on nameplate capacities and modelled load which do not accurately represent the actual capacity requirements. It is challenging to understand the impact of changes that are made in real-time.

Thermal and Air Management metrics monitor environmental conditions inside the data center. These metrics give an overview of how efficiently air flows within a data center and also quantify the extent of cold and hot air mixing. Continuous monitoring of these metrics allows the operators to reduce fan speed and increase cooling set points in real-time, which increases cooling efficiency and energy savings. It is difficult to determine the correct values for temperature and humidity in the data center, as the environment is dynamic and constantly changing.

Network metrics cover the network energy efficiency, network utilization and traffic demands of a data center. Networking equipment is responsible for a large portion of a data center's energy consumption, therefore it is important to optimize the efficiency of the equipment.

Security metrics cover aspects such as the firewall performance. These metrics are highly dependent on internal governance, compliance standards and service level agreements of the data center in question. Another issue is authorization: the visibility of and control over resources in a data center.

Storage metrics capture the performance of storage operations. These metrics assist the operators in reducing storage cost, improving storage utilization and increasing the overall storage performance. The distributed nature of cloud computing makes it critical to learn what workloads customers are accessing and the level of importance of the accessed data.

Financial Impact metrics help achieve a data center's financial and strategic objectives. These metrics range from total cost of ownership to return on investments. Measuring business value may vary from one organization to another due to different definitions, and Carbon Credit may vary based on a country's policies.

5 Conclusion

Metrics are important for planning, designing, building and operating a data center in an efficient manner. Our classification of metrics provides deep insights into the state-of-the-art of measuring different data center components. Our study on the most adopted and representative metrics currently in use throughout the data center industry revealed that the use of these metrics is critical to enable monitoring the data center efficiency in a timely manner, aiming to minimize energy consumption and total cost of ownership. Our proposed classification allows for quick access to the right subset of metrics from a huge collection that fits the desired context.

Measurement of thermal, airflow and cooling metrics is easy to automate using manually collected data or data automatically gathered from sensors. Energy efficiency, performance, network and storage metrics can be used to increase the operational efficiency. So called green metrics can be used to decrease the environmental impact of data centers. However, in all cases, it is crucial to use accurate data as input.

As there is a wide range of different metrics available for data centers it would be beneficial if there was an automated process to collect, process and analyze the data and use it to automatically calculate all available metrics. Such an automated process can take advantage of the Internet of Things philosophy by connecting numerous sensors together to create one platform. It can also maintain the history of sensor data and provide different types of analytics on top. Such a platform can potentially discover new correlations between data sets. The data can also be used to decide whether the existing technology and equipment can be used more efficiently, e.g., improved scheduling algorithms, or whether it is better to replace them with the latest, most efficient technology or equipment.

We observed that existing metrics are mainly focused on measuring the energy efficiency of IT equipment or facilities. Older facilities may not be able to capture the raw data that feeds today's more sophisticated metrics. There are very few metrics defined which can integrate different components of the data center that have a single numerical value to report the efficiency of the data center in all perspectives. Also, there is no metric which reflects the changes made to a data center and its sub-components. Furthermore, there is a need for new metrics that consider different factors such as the location and age of the data center, in order to allow comparison across different data centers.

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