A Survey on Metrics and Measurement Tools for Sustainable Distributed Cloud Networks

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***Abstract*—Energy efficiency and emissions awareness are core capabilities for sustainable and lower cost distributed cloud networks. In this context, metrics are fundamental for comparison and management purposes, along with the methods and tools which support such metrics' capture and analysis. However, prior works on green metrics and tools have presented only a partial view, mainly as a result of the recent advances in green networking technologies. In this survey, we present an extensive study of metrics, methods, and tools to support sustainable operations in distributed cloud networks, with the aim of providing an end-to-end and up-to-date scenario to support current and coming research, as well as to analyze existing gaps.**

***Index Terms*—Distributed Cloud Networks, Network Management, Metrics, Methods, Measurement, Sustainability**

I. INTRODUCTION

Distributed clouds are emerging in response of application requirements that include delivering content with low latency and enabling a high degree of scalability to support immense quantities of data expected to be generated by 29 billion devices predicted to be interconnected by 2020 [1]. Regulatory compliance constraints as well as autonomy and security constraints associated with industrial facilities and telecommunication networks deploying virtualized network functions also add to the demand for distributing clouds. Such clouds are decentralized in many geographical locations, with each location consisting in small numbers of compute, network and storage resources along with associated facility management capabilities such as cooling and air conditioning. In contrast with the huge centralized clouds, deployed on geographically distributed large datacenters housing in the order of tens of thousands servers, distributed cloud locations may support as little as a few servers (for example, micro-clouds located at mobile telecommunication networks Points-of-Presence such as mobile base stations) and scale up to a few racks of compute and network equipment, like for example those proposed by CORD (Central Office Re-architected as a Datacenter) architectures that recommend up to sixteen racks of equipment in each location [2].

The geographical diversity of distributed cloud locations in many cases translates onto differences in terms of energy costs between the locations of the datacenters. In centralized clouds, the entire datacenter is powered by typically one dominant energy source, which in many cases is produced close by at a large-scale power plant with highly predictable availability of the energy source (be it hydro-electrical, coal, nuclear power or solar energy in locations that average a significant number of days with cloud-free skies). Distributed clouds, in contrast, are powered by a combination of electricity transferred via regional or national grids and sourced from a multitude of sources, with mixtures that exhibit regional and country-specific characteristics. In some cases, small local deployments of renewable energy-producing equipment such as solar panels or wind turbines as well as diesel generators complement the grid and ensure certain levels of reliability in cases when the main power infrastructure is unreliable. The availability of a particular type of energy source is thus more of a concern in distributed clouds.

Energy storage solutions (such as batteries) have enough capacity to power an entire location of a distributed cloud for reasonable time intervals, for example compensating for the lack of solar energy during the night, while it is just not feasible, at the moment of writing this paper, to consider powering a large centralized cloud facility only on batteries for one night. Therefore, in addition to knowing the source of the power, accurate measurements or predictions of its availability are needed in order to optimize energy-efficient operations in distributed clouds. The distribution of compute workloads could be made such that it maximizes the energy consumption on sites powered by renewable energy that cannot be stored, as shown by Camus et al. in [3] for sites equipped with photovoltaic panels.

At the other end of the spectrum, when the power source is soon becoming unavailable and there is no possibility to source additional electricity, the workload should be migrated from the site to ensure uninterrupted service. Optimizing this process requires accurate methods to provide estimates of the power remaining, precise data on the power consumption associated to migrating the workload as well as an understanding of the geographical extent of the power unavailability. In contrast, centralized clouds focus on migration techniques for optimizing the overall power consumption and the power expenditure during the migration is just one of the costs accounted for as part of the optimization. A taxonomy of techniques for providing energy efficiency in distributed clouds was made by Khosravi and Buyya in [4].

As outlined in the NRDC report, in 2014 only less than 5% of the cloud energy usage came from what we refer to

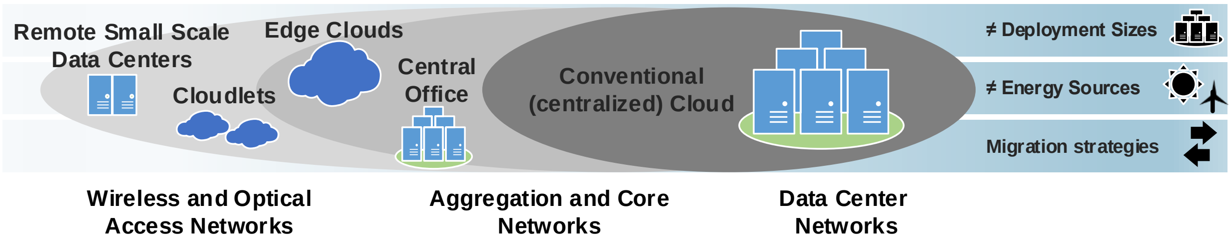

Fig. 1. Distributed Cloud Networks: the scope of this survey

as centralized data centers [5]. The remaining more than 95% of the power consumption came from facilities that in their majority would fit our definition of distributed cloud locations, which further on in many cases are mixed-use buildings. In a mixed-use building, a significant part of the space is allocated to, for example, offices, with the datacenter located in the basement of the building but sharing critical infrastructure such as the air conditioning systems. A known problem in such locations is the lack of coordination between the load management systems of the cloud infrastructure and of the office facilities, resulting in energy inefficiencies such as those addressed for example by Wei et al. [6]. From a pure metrics and measurement tools perspective, this triggers a requirement for interactions between different energy measurement systems that would attempt to optimize for different values of the same metric (such as operating temperature).

From an application perspective, it is a common scenario that all the services involved in one application are executing from the same centralized cloud location (perhaps with the notable exception of content cached by distribution networks). However, in the case of a distributed cloud, different services that compose an application are more likely served from different datacenters. For telecom networks that operate distributed cloud locations for virtual network functions, different virtual function instances that are part of one service would be executed in many datacenters – some of them closer to the user, some of them in a more central location. Chou et al. [7] suggest a method for minimizing the electricity costs while optimizing the tail latencies of a distributed application. Their method uses standard energy consumption models and ignores the energy costs of the data transfers. As such, in distributed clouds, there is a need for composite metrics that would facilitate understanding of the transit delays incurred by decentralizing a particular service when optimizing energy consumption. This would also give ideas of the electricity costs associated with the long-distance transmission of the data, which might not be immediately available to the administrative domain to which the application belongs to.

These metrics should put together information about different performance and sustainability aspects, either from an energy point of view, or from a GreenHouse Gases (GHG) emissions point of view. This is challenging because, despite research and industry efforts, a set of most appropriate metrics is still open. Moreover, a set of methods and tools to fully support the capturing and analyzing of such metrics is an effort that is under way.

In this survey, we present an extensive study of metrics and measurement methods/tools to support sustainable operations in distributed cloud networks, as depicted in Figure 1. Previous surveys of green networking technologies like [8] and [9] covered metrics only in a partial manner at the time when they were written, and many notable developments have happened since. Now there are so many metrics and ways to measure them that they merit a separate survey, which is what we are providing. A comprehensive survey in this context contributes to the research in the area by providing information and a classification with comments on usage and gaps to be filled to support the current and coming research work. Such a survey could also create opportunities for novel ways in which to interconnect sub-segments or rationalize the number of measurements that actually need to be carried out.

The remainder of this paper is structured as follows. In Section II we detail the background used to evaluate the surveyed works. In Section III, we review the metrics proposed by standardization bodies, consortia, companies and other research groups, and we discuss and analyze the relationships among them. In Section IV we review and discuss the existing measurement methods and tools for monitoring and measuring power/energy and emissions. The final remarks are presented in Section V.

II. BACKGROUND

To be compliant with governmental goals and regulations on energy efficiency and emissions, service providers need a monitoring infrastructure composed of different layers and frameworks, converging into a couple of objectives designed to align with those energy efficiency and emissions requirements. A classification of metrics, methods, and tools by scope of usage is relevant to help build consensus on the type of information that is exchanged between different entities and the level of aggregation expected from each network's scope. Relying upon prior work and new technologies, as well as previous surveys [8] [9], we use throughout this paper the classification illustrated in Figure 2. The government-defined policies mentioned on the top of the framework embed significant political aspects and, therefore, are not covered in this technically-centered publication.

Corporate: or business-level, is the highest level and is responsible for implementing high-level metrics based on data collected from service provider facilities and reporting sustainability data that is required to be in compliance with governmental rules. At this level, reports are typically generated and delivered on a daily to yearly basis.

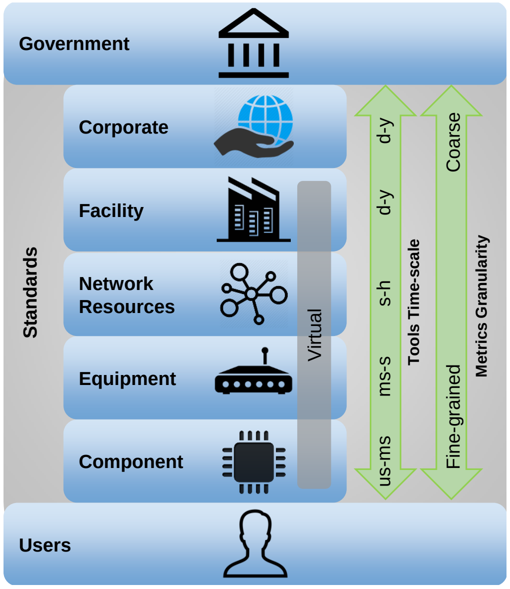

Fig. 2. Scope of the metrics, methods, and tools presented in this work

Facility: is a physical unit comprising several resources, such as networking, computing, and storage. A facility could be a small infrastructure (*e.g.*, cloudlet, room with servers, networking equipment, and cooling) or a larger-scale data center with many resources. Metrics implemented at this level might consider the ratio between the achieved overall facility performance level (*e.g.*, data center load capacity), taking as input data collected from its various resources, and the overall power supplied from the UPS (Uninterruptible Power Supply) system. Reports are usually done on a minute, hourly, or daily basis. For instance, the Facebook Prineville Datacenter [10] reports metrics such as PUE (Power Usage Effectiveness) and WUE (Water Usage Effectiveness) online on a minute basis.

Network: comprises metrics of various networking resources and frameworks in a facility, implemented in software or hardware. At this level, metrics can aggregate energy efficiency data from various devices to be reported to the facility level, which demands the development of different southbound interfaces to obtain energy-related information from network devices. Measurement times at the network layer usually range from seconds to hours.

Equipment: metrics at this level represent the efficiency of different devices, such as a switch, a router, a base station. As an effort toward standardization, IETF proposed several RFCs (Request for Comments) to standardize MIBs (Management Information Bases) for storing energy-related information, such as device power states, energy consumption, and battery usage. Measurement times at this layer usually range from milliseconds (ms) to minutes.

Component: metrics at this level represent components inside a piece of equipment and are highly dependent on the hardware or software capabilities provided by the manufacturers. At this level, a common approach is to obtain performance data from interfaces or packet processors via manufacturer-specific APIs and to store them in a local database for processing. At this level, information regarding device performance or consumption from a power supply module are usually obtained in the order of microseconds (μs) to milliseconds (ms).

Selected references, such as [11], [12], and [9], mention metrics at the user-level as a share within the entire infrastructure or being related to the Quality of Service (QoS), energy, or emissions. In this case, these metrics rely heavily on the service model implemented by the service provider. There are also efforts to provide specialized service levels based on user-specific energy requirements. For instance, a customer may specify a percentage of green energy to be used in the execution of data center workloads [13]. The method relies on the availability of renewable energy sources. Another common approach is to evenly divide an entire network or an equipment metric by the number of lines or users. A weighted approach can also be considered, given the level of service each user hires. At this level, information is generally obtained monthly (billing cycle), but could easily be performed on different timescales, depending on contracts and the amount of information required.

Sources in the literature also define application-level metrics, e.g., [14]. Such metrics could be used by developers or application users to be aware and take informed decisions about performance, energy, and GHG emissions. In this context, the information timescale will depend heavily on the nature of activities being performed and whether they are critical (e.g., millisecond timescale for 5G and applications it will enable) or not.

It is important to note that current virtualization techniques play a fundamental role in different scopes, that are the abstraction layers in which a sustainable metric or tool can be deployed within an organization as illustrated in Figure 2. For example, both facility-level data centers and entire equipment and network infrastructures can be virtualized, making it easier to evaluate new methods and tools to obtain metrics for energy efficiency. In this sense, virtualization is not a scope by itself, but can be seen as a method adopted in the listed scopes.

III. SUSTAINABILITY METRICS

Monitoring and measurement are fundamental tasks to evaluate network sustainability, and metrics are at the kernel of these activities. A metric is a measured quantity of a particular network characteristic related to the system's performance, reliability, energy efficiency or GreenHouse Gases (GHG) emissions. Key Performance Indicators (KPIs) are specific metrics used to evaluate performance according to a company's goals. Metrics can vary according to the granularity of measurements in the different network scopes (*e.g., device-level or network-level*) in which a characteristic is measured. In particular, metrics for energy efficiency are usually defined as the ratio between the service delivered by a network "item" and the required energy during a certain measurement time period [15]. Energy-efficiency metrics can be either *absolute*, indicating the energy consumed given the performance, or *relative*, showing how energy efficiency can be improved, by comparison. For the former, $bits/Joule$ is a common metric example; for the latter, the ratio of output and input power in power amplifiers is a case [16].

In this section, we review prior work regarding metrics definition and usage proposals from consortia, companies, research groups, and the following standardization bodies: ISO (International Standards Organization), ETSI (European Telecommunications Standards Institute), ITU (International Telecommunication Union), ATIS (Alliance for Telecommunications Industry Solutions), and IETF (Internet Engineering Task Force).

A. Corporate-level Metrics

Corporate-level metrics may include the simple GHG emissions measured in gCO_2e for reporting purposes or more elaborate constructs. The emissions are divided in direct (Scope 1), indirect from electricity (Scope 2), and other indirect (Scope 3) [17]. Verizon proposed $Carbon\ Intensity$ [18], represented by the division of Scope 1 and 2 emissions by the total data transported over its networks ($CO_2e/Terabyte$), defined in (1). Akamai reports a similar value in $tonCO_2/Gbps$ of data delivered [19].

$$Carbon\ Intensity = \frac{GHG\ emissions\ Scope\ 1\ and\ 2}{Terabytes\ of\ data\ traffic} \tag{1}$$

eBay proposed the Digital Service Efficiency (DSE) as a way to monitor cost, performance, and environmental impacts of customer transactions (buy and sell) using the company's infrastructure (data centers composed of servers, storage, and network). After identifying the top-level services (which, in eBay's case can be translated to a set of URLs to deliver a service), they quantify the energy consumed for each service, direct and indirectly, comprising the supporting infrastructure. The energy consumed, in conjunction with the number of transactions, can then be used to evaluate performance, cost, revenue, and environmental impact. They also mention the use of PUE [20] for their facilities, explained in the next subsection. Erol-Kantarci and Mouftah [21] suggest to extend DSE to Green Digital Service Efficiency ($GDSE$) to account for renewable sources per transaction, given that some renewables feeding the data center are known.

B. Facility-level Metrics

In 2014, the Green Grid consortium task force recommended a set of metrics for data centers that include the process for measurement of each metric [22]. The metrics are for data centers but could be applied to network sites or central offices. The first recommended metric is DCeP (Data Center energy Productivity), which measures the useful work that a data center produces compared to the energy consumed łby the datacenter while excuting the useful work. Equation 2 describes this metric. The second metric is PUE (Power Usage Effectiveness), defined in (3).

$$DCeP = \frac{Useful\ Work\ Produced}{Energy\ Consumed}, \tag{2}$$

$$Useful\ Work\ Produced = \sum_{i=1}^{M} V_i * U_i(t,T) * T_i$$

where M represents the tasks initiated during the test period; V_i is a normalization factor which allows to sum tasks numerically; T_i equals to 1 if task i completes during the test period, and T_i equals to zero if it does not; $U_i(t,T)$ is the time-based utility function for each task; t is the elapsed time; and T is the absolute time to complete the task.

$$PUE = \frac{Total\ Facility\ Power}{IT\ Equipment\ Power} \tag{3}$$

The list concludes with three other metrics that data centers should measure: GEC[1] (Green Energy Coefficient), which quantifies the percentage of energy in a data center from certified green sources; ERF (Energy Reuse Factor), which corresponds to the share of energy that is exported for reuse externally to the data center; and CUE (Carbon Usage Effectiveness), the total GHG emissions of a data center (including electricity, renewable energy produced locally, and other primary energy sources) divided by its ICT energy consumption (only usage emissions, direct and indirect from electricity bought [17]). When electricity is the only energy source, it is equal to the PUE multiplied by the location emission factor. Equations [4-6] describe these three metrics. GEC has a maximum value of 1.0 corresponding to 100% of green energy; ERF ranges from 0.0 to 1.0, and CUE is given in $kgCO_2eq$, being ideally equal to zero.

$$GEC = \frac{Green\ Energy\ Used\ by\ the\ Data\ Center}{Total\ Data\ Center\ Source\ Energy} \tag{4}$$

$$ERF = \frac{Reuse\ Energy\ Outside\ of\ the\ Data\ Center}{Total\ Data\ Center\ Source\ Energy} \tag{5}$$

$$CUE = \frac{Total\ CO_2\ Emissions}{IT\ Equipment\ Energy} \tag{6}$$

Besides the metrics related to energy efficiency and GHG emissions, Green Grid also discussed in detail three other metrics related to performance: network traffic (bits) per watt-hour, weighted CPU utilization, and IT equipment energy efficiency versus IT equipment utilization.

The metrics proposed in the ECO-CLOUD Project [23], which focused on cloud data center metrics, are of the following types: power-related (which actually evaluate energy efficiency), performance-related, and network traffic-related. The power-related metric suggested for the facility-level is NPUE (Network Power Usage Effectiveness), which measures the part of the power consumed by all IT equipment that goes into the network, as described in (7).

$$NPUE = \frac{Total\ Power\ Consumed\ by\ IT\ Equip.}{Power\ Consumed\ by\ Network\ Equip.} \tag{7}$$

The ISO Subcommittee (SC) 39 [24], which also works with ITU, ETSI, and the Green Grid consortium, defines KPIs

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[1] When it comes to *green* energy sources, Green Grid recommends the usage of local/regional authority certificates to attest that the energy is from renewable sources.

for data centers under the ISO 30134 series. They suggest employing:

- PUE (Power Usage Effectiveness);
- REF (Renewable Energy Factor), similar to the Green Energy Coefficient;
- ERF (Energy Reuse Factor);
- ITEE (IT Equipment Energy Efficiency), detailed in (8); and
- ITEU (IT Equipment Utilization), in percentage.

$$ITEE = \frac{Total\ IT\ equipment\ capacity}{Total\ IT\ equipment\ energy\ consumption} \tag{8}$$

Mitchell *et al.* [25] report the metric $Watts/m^2$ or $Watts/ft^2$ as a common metric when it comes to power in data centers. However, the authors state that the metric is often unclear because the numerator and the denominator vary according to the use. Besides, usual computer power density calculations only include the power drawn by the computer equipment, but not the power required by the supporting systems, which, therefore, does not indicate the total power needs of the data center under analysis. As a better estimate, the authors suggest to use the *total computer room power density*, the power drawn by the ICT equipment and all of the supporting equipment in Watts divided by the floor area of the equipment room.

Sun proposes the SWaP (Space, Watts, and Performance) metric for data center; it divides the performance measured by using industry standard benchmarks by the multiplication of the height of the servers in rack units and the power consumption, which is calculated using data from benchmarks [26]. The metric can be applied to networking equipment.

HP Labs proposed the Datacenter Water Usage Energy Metric (ω) [27], which takes into consideration the energy footprint of water consumption, that is, the energy for treatment and distribution of water to the location in which it will be used. It includes direct (for cooling) and indirect (for power generation) usage. Equation 9 describes the metric. The power consumptions represent the average power over a predefined period. There are other metrics for data centers that are related to the facility itself, such as humidity or thermal aspects [26].

$$\omega = \frac{W_D + W_I}{Power\ Consumed\ by\ IT\ equipment} * 10^3 \tag{9}$$

where W_D is the power consumption from direct water usage and W_I is the power consumption from indirect water usage.

The EARTH Project (Energy Aware Radio and neTwork tecHnologies) lists in [28] the most suitable metrics and utility functions inside the project scope. For the facility scope, the document cites PUE and DCiE, a reciprocal of PUE ($1/PUE$).

ETSI "ES 205 200" series covers energy use management. Part 1 presents the general requirements, while Part 2 presents the specific requirements for data centers, fixed, and mobile networks. Part 3 presents the "Objective KPIs" defined in Part 2 in a simple format and uses them to define a Global KPI for ICT sites. The document also details the measurement points and processes that must be followed [29]. The aim is to address the objectives of (i) energy consumption, (ii) task efficiency, (iii) energy re-use, and (iv) renewable energy. Equations [10-13] describe the objective KPIs for ICT sites' operation.

$$KPI_{EC} = EC_{REN} + EC_{FEN} \tag{10}$$

$$KPI_{TE} = \frac{KPI_{EC}}{EC_{HE}} \tag{11}$$

$$KPI_{REUSE} = \frac{EC_{REUSE}}{KPI_{EC}} \tag{12}$$

$$KPI_{REN} = \frac{EC_{REN}}{KPI_{EC}} \tag{13}$$

KPI_{EC} (in MWh) is the energy consumption objective KPI, the dominant part of the calculations. EC_{REN} is the annual energy consumption from renewables (locally produced or from the grid); EC_{FEN} is the annual energy consumption from other power sources. KPI_{TE} (dimensionless) is the task efficiency defined by the ratio of KPI_{EC} to EC_{HE}, the annual energy consumed by "equipment that manage data for calculation, storage or transport purposes". A common value for this KPI is between 2 and 2.5 [29]. KPI_{REUSE} (dimensionless) is KPI_{EC}, the annual amount of reused energy outside the ICT site divided by KPI_{EC}. Thermal energy can be reused in different ways, for water or office heating, among others. KPI_{REN} (dimensionless) is EC_{REN} divided by KPI_{EC}. Only the sources contributing to KPI_{EC} (dedicated or shared) should be taken into account.

The Global KPI DC_{EM} (Data Processing and Communications Energy Management) is composed of two values: DC_{EC}, the annual energy consumption by a single or a group of ICT sites, and DC_{CLASS}, the energy performance class expressed as a letter. For a single ICT site, DC_{CLASS} is defined according to DC_P, the energy use management performance, for a given DC_G, the energy consumption gauge. DC_G is defined according to the range values of KPI_{EC} (e.g., $DC_G = XS\ for\ 0.04GWh < KPI_{EC} \leq 0,2GWh$). Each gauge has the weighting factors W_{REUSE} and W_{REN} associated with it, which are used to calculate DC_P as in (14). With DC_P, it is possible to determine the energy performance class DC_{CLASS}, as depicted in Table I.

$$\begin{aligned} DC_P = KPI_{TE} * \\ (1 - W_{REUSE} * KPI_{REUSE}) * \\ (1 - W_{REN} * KPI_{REN}) \end{aligned} \tag{14}$$

TABLE I
DEFAULT CLASSES [29]

	DC_P	
DC_{CLASS}	>=	<
A		1,00
B	1,00	1,40
C	1,40	1,70
D	1,70	1,90
E	1,90	2,10
F	2,10	2,30
G	2,30	

For a group of sites, DC_{EC} is defined as in (15), where i is the site, and n, the number of sites. DC_{CLASS} is defined as in (16). For DC_{CLASS} in this calculation, class letters are translated to their rank, *i.e.*, $A = 1, B = 2$; DC_{CLASS} is expressed as a letter. Table II illustrates the construction of DC_{EM}.

$$DC_{EC} = \sum_{i=1}^{n} KPI_{EC}(i) \tag{15}$$

$$DC_{CLASS} = \frac{\sum_{i=1}^{n} DC_{CLASS}(i) * KPI_{EC}(i)}{\sum_{i=1}^{n} KPI_{EC}(i)} \tag{16}$$

TABLE II
DC_{EM} CONSTRUCTION

Objective KPIs	**Intermediate KPIs**	**Global KPI**
KPI_{EC}	DC_G	$DC_{EM}\ [DC_G; DC_P]$
KPI_{TE}	DC_P	
KPI_{REUSE}		
KPI_{REN}		

C. Network-level Metrics

In the technical specification “TS 102 533” (“Measurement Methods and limits for Energy Consumption in Broadband Telecommunication Networks Equipment”) [30], ETSI defines NPC (Normalized Power Consumption), an indicator of the global network power performance in $mW/Mbps/km$, as described in (17).

$$NPC = \frac{1000 * P_{BBline}}{(bitrate * line\ length)} \tag{17}$$

Han *et al.* [31] propose the ECG (Energy Consumption Gain), a ratio between the baseline system energy consumption E_b and the system under test energy consumption E_t. The greater the ECG, the more efficient the system under test. The authors complement this by saying that care must be taken to ensure that the energy calculations are performed in a fair manner, for instance, using the same traffic load conditions.

In the Technical Specification “TS 102 706” (“Measurement Method for Energy Efficiency of Wireless Access Network Equipment”) [32], ETSI specifies, for a GSM network, the metric described in (18) to measure the coverage of the network in a rural area. For urban areas, the formula is related to the number of users, as described in (19).

$$EE_{coverage} = \frac{A_{coverage}}{P_{site}} \tag{18}$$

$$EE_{capacity} = \frac{N_{busy\_hour}}{P_{site}} \tag{19}$$

where $A_{coverage}$ is the RBS (Radio Base Station) coverage area in a rural area (km^2) and N_{busy_hour} is the number of subscribers on the average busy hour.

For WCDMA/LTE/WiMax, the metric is more complex. For the x^{th} activity level, the power consumption of the RBS is sampled every 0.5 seconds or less during the test. The tests are repeated n times, referring to the total number of duty cycles during the trial. Then the average energy is calculated over n repetitions multiplied by the period. For the distributed scenario, there is also the addition of the energy consumed by remote and central parts. To obtain the last metric in $kbits/J$, it is necessary to divide the average net data volume by the energy value calculated previously [32].

In the standard “ES 201 554” (“Measurement method for Energy Efficiency of Mobile Core Network and Radio Access Control equipment”) [33], ETSI not only details the measurement methods for such devices, but also mentions some metrics for core networks: site energy consumption, power consumption at different load levels, and energy efficiency, dividing the useful output per number of Erlangs, or per $Packets/s$, per subscribers or simultaneously attached users.

In the standard “ES 203 228” (“Assessment of mobile network energy efficiency”) [34], ETSI defines metrics for Mobile Radio Access Network (MN). The Mobile Network data Energy Efficiency ($EE_{MN,DV}$), in bit/J, is described in (20).

$$EE_{MN,DV} = \frac{DV_{MN}}{EC_{MN}} \tag{20}$$

where EC_{MN} is the energy consumption comprising all base stations of the mobile network under evaluation, all the site’s infrastructures (cooling equipment, battery losses, illumination, etc.), backhauling providing connection to the base stations, and control nodes. DV_{MN} is the data volume delivered by the equipment during the testing period (a week, a month, or a year). It should include packets, and circuit switched services, like voice.

The same document defines the Mobile Network coverage Energy Efficiency ($EE_{MN,CoA}$) in m^2/J, shown in (21), used to complement $EE_{MN,DV}$ for networks handling low volumes of data, as in rural areas. EC_{MN} is the yearly energy consumption.

$$EE_{MN,DV} = \frac{coverage\ area}{EC_{MN}} \tag{21}$$

Recommendation ITU-T L.1330 [35] provides a set of metrics and methods for mobile networks. It includes radio base stations, backhauling systems, radio controllers, and other infrastructure radio site equipment (*e.g.*, air conditioning, fixed network equipment). For individual equipment, the document references L.1310 [36] because of the focus of L.1330 on the whole wireless network. ITU-T L.1330 is technically equivalent to ETSI “ES 203 228” [34]. The standard was developed in cooperation with ETSI and in association with 3GPP and the GSM Association (GSMA).

The EARTH Project [28] cites TEEER, an equipment metric, and ETSI methods on obtaining P_{site}, the site average power consumption for concentrated and distributed RBS. Then, using P_{site}, they define the Energy Consumption Index (ECI) as the ratio between P_{site} and coverage or throughput. If using coverage, it is the inverse of $EE_{coverage}$, defined in the ETSI document they use as a reference [32]. They cite the ETSI metrics for rural and urban areas from this document [32]. The EARTH Project [28] also mentions the traditional energy consumption per bit, the Power per Area Unit expressed in W/m^2 (which they state is of particular interest for the project, also explored in [37]), and Power per Subscriber, which may have disadvantages because it is not always clear which subscriber is being referred. For instance, just a fraction of the entire population of subscribers is usually active at a given time.

A survey focusing on Information-Centric Networking (ICN) [38] introduced, besides a list of traditional networking metrics, a list of energy efficiency metrics used in ICN. The authors state that the common metrics in this case are:

- Total energy consumption, in J;
- ESR (Energy Saving Rate), in %, given by the ratio of the "saved energy by in-network caching in ICN to the total energy consumption incurred without caching";
- Network Energy per Bit, in J/bit, calculated as a ratio of network energy consumption to request rate.

The authors also include a widely accepted metric to evaluate the trade-offs between energy efficiency and performance: EDP (Energy-Delay Product), measured in J/s [39]. Equations 22 and 23 compare the cached content in relation to the content provided by the source, where $DataSize$ is content size, D the link delay per size unit to move data across the link, and T_{cached} the lifetime of the content in the cache. The objective is that $EDP_{cached} < EDP_{from\_source}$.

$$\begin{aligned} EDP_{from\_source} &= Energy * Delay \\ Energy &= K * N * E_{link} * DataSize \\ Delay &= K * N * D * DataSize \end{aligned} \tag{22}$$

$$\begin{aligned} EDP_{cached} &= Energy * Delay \\ Energy &= DataSize * \\ (K * M * E_{link} &+ T_{cached} * P_{store}) \\ Delay &= K * M * D * DataSize \end{aligned} \tag{23}$$

D. Equipment-level Metrics

The Energy Consumption Rating (ECR) Initiative proposed the ECR metric [40] in conjunction with a method to measure and report the energy efficiency for different classes of networking equipment. The primary metric is ECR, as described in (24), which represents the energy necessary to move n Gbps of user data in $W/Gbps$ [41]. The secondary metric is a synthetic metric, ECRW (Energy Consumption Rating Weighted) [42], described in (25).

$$ECR = \frac{E_f}{T_f} \tag{24}$$

$$ECRW = \frac{((\alpha * E_f) + (\beta * E_h) + (\gamma * E_i))}{T_f} \tag{25}$$

where T_f is the maximum throughput (in Gbps) during the test; E_f is the energy consumption (in Watts) during the test; E_h is the energy consumption during half-load test; E_i is the energy consumption during idle test; $\alpha = 0.35$, $\beta = 0.4$, and $\gamma = 0.25$ are the coefficients to represent the mixed mode of operation.

HP Labs proposed the EPI (Energy Proportionality Index) [43]. The idea of the metric is to represent the difference between ideal and measured power consumed by the equipment. The metric is defined as $EPI = (M - I)/(M) * 100$, in percentage. If $EPI = 100$, the device is totally energy proportional, while if $EPI = 0$, the equipment is agnostic to the load [43].

The ECO-CLOUD Project [23] suggests, for the equipment-level scope, the CNEE (Communication Network Energy Efficiency), similar to the previously described ECR, in $Watts/bit/second$, described in (26); and the EPC (Energy Proportionality Coefficient), measured as the energy consumption as a function of the load, described in (27). It is different from the known EPI, which depends on idle and peak power consumption. EPC can differentiate continuous and non-constant functions when evaluating the load proportionality of equipment.

$$CNEE = \frac{Power\ Consumed\ by\ Netw.\ Equipment}{Effective\ Netw.\ Throughput\ Capacity} \tag{26}$$

$$EPC = \int_0^1 \frac{2tan\alpha}{1 + tan^2\alpha}\, dl,\ tan\alpha = \frac{dP}{dl} \tag{27}$$

where P is the power consumption and l, the normalized load.

In the draft [44], IETF defines the device NECR (Network Energy Consumption Rate) in $milliWatts/Mbps$, dependent on the line card, port, and other factors. The document also states that the efficient use of this metric depends on the specification of the base power (when there is no load) of the chassis, line card, and port. The document defines the NEPI (Network Energy Proportionality Index), aligned to the ideal situation in which the power consumed by a device is proportional to the load it handles. The difference between the ideal value and the measured power consumed defines the EPI. The EPI/NEPI equals to zero if the equipment power consumption is not influenced by traffic and to 100 if the device is ideally energy proportional (linear dependency between load and energy consumption).

ATIS proposed the TEER (Telecommunications Energy Efficiency Ratio), defined as $Useful\ work/Power$, varying according to the type of equipment under evaluation and considering different workloads. [45] lists some examples for various equipment types: transport equipment (28), switches and routers (29), access equipment (30), power sources (31), and power amplifiers (32).

$$\frac{-log(P_{total})}{Throughput}\ [in\ dB/Gbps] \tag{28}$$

$$\frac{log(P_{total})}{ForwardingCapacity}\ [in\ dB/Gbps] \tag{29}$$

$$\frac{No.of AccessLines}{P_{total}} \tag{30}$$

$$\frac{P_{out,total}}{P_{in,total}} \tag{31}$$

$$\frac{P_{RF,out}}{P_{Total,in}} \tag{32}$$

There are two types of TEER: $TEER_{declared}$ and $TEER_{certified}$, measured for specific configurations, in $Mbps/W$. Both can be calculated using the formula described in (33).

$$TEER = \frac{\sum D_i}{(P_0 + P_{50} + P_{100})/3} \tag{33}$$

where D_i is the data rate at a given interface; P is the measured power consumption (W), and $0/50/100$ are the data traffic utilization levels in which the measurement are captured.

In Recommendation ITU-T L.1310 [36], ITU specifies the "principles and concepts of energy efficiency metrics and analysis methods for telecommunication network equipment." They define the EER (Energy Efficiency Ratio) according to ATIS TEER, measured in bits per seconds per Watts (Gbps/Watts). Equation 34 describes this metric.

$$EER = \frac{T_i}{P_w}, \tag{34}$$

$$T_i = a * T_{u1} + b * T_{u2} + c * T_{u3},$$
$$P_w = a * P_{u1} + b * P_{u2} + c * P_{u3}$$

where T_i is the weighted throughput and P_w is the weighted power; a, b, c are the weights for the different utilization levels; P_{u1}, P_{u2}, P_{u3} represent the power measured for each utilization levels; and T_{u1}, T_{u2}, T_{u3} represents the throughput for the different utilization levels.

The document refers to ATIS for more details on total throughput, testing topologies, and traffic patterns. EER uses weighted throughput and weighted power to sum the values for different levels of utilization, depending on the equipment, with more various levels of use than ATIS. There are different profiles for routers, switches, small networking devices, and for optical/transport equipment, as listed in Table III.

For small networking devices (home and small office), EER is calculated as in (35). For interfaces with throughput T sensitive to distance, $T = 0.5(T_{20\%\ of\ max\ distance} + T_{80\%\ of\ max\ distance})$. The document also specifies the intervals at which the measurements should be taken and the test methodologies for small networking devices. For wireless access equipment, ITU references ETSI "TS 102 706" for the measurement method. There are different types of metrics according to coverage and traffic, a static or dynamic mode for Radio Base Stations. The metrics and test methods for transport equipment, excluding microwave radio equipment, are based on ATIS. For the converged packet, optical equipment it is also based on ATIS TEER, but composed by the packet throughput and TDM functions, as described in (36). And, specifically for converged packet optical equipment with packet signal, TDM signal and WDM signal functions, (37) accounts for packet (throughput A), TDM (B), and WDM (C and add/drop rate α) functions.

$$EER = \frac{0.35Tidle + 0.5Tlowpower + 0.15TMax}{0.35Pidle + 0.5Plowpower + 0.15PMax} \tag{35}$$

$$EER = \frac{\sqrt{\frac{A^2+B^2}{2}}}{\left\{\frac{(P_{idle}+P_{max})}{2}\right\}} \tag{36}$$

$$EER = \frac{\sqrt{\frac{A^2+B^2+(C*\alpha)^2}{3}}}{\left\{\frac{(P_{idle}+P_{max})}{2}\right\}} \tag{37}$$

In the standard "ES 203 184" ("Measurement Methods for Power Consumption in Transport Telecommunication Networks Equipment") [46], ETSI proposed the EEER (Equipment Energy Efficiency Ratio) for Transport equipment, as described in (38) in $Mbps/W$. This metric is calculated with the same formula as the TEER from ATIS, but following the measurement conditions presented in the ETSI document.

$$EEER = \frac{B}{P} \tag{38}$$

where B is the sum of the interface data rates and P is the power consumption as $P = (P_{0\%} + P_{50\%} + P_{100\%})/3$.

Using the ATIS recommendations as reference, Verizon defined the TEEER (Telecommunication Equipment Energy Efficiency Rating) [47]. TEEER is an average rating of the power consumption at 0%, 50%, and 100% utilization levels [48]. The company uses the ATIS methods for different equipment types and applies correction factors to the ATIS TEER values to obtain the Verizon TEEER values, as described in Table IV. The document also gives the general conditions to perform the measurements.

TABLE IV
VERIZON NEBS CORRECTION FACTOR [47]

Equipment Type	**Correction Factor**
Server	TEER / 10
Transport	-log (1 / (TEER * 1000000))
Router and Ethernet Switch	-log (1 / (TEER * 1000000))
Rectifier	TEER / 100
Wireline Access	Report TEER
Small Network Equipment	Report TEER
Base station	Report TEER
Inverter	TEER / 100

Juniper defines the CCR (Consumer Consumption Ratio) metric [49] as a way to describe consumer network equipment of any kind. It is dimensionless and a value of 1 matches an average device. Equation 39 describes this metric. E is the power consumption of a consumer network device, A is the energy fee per function (*e.g.*, DSL, WiFi), and J is the set of all allowances that can be claimed.

$$CCR = \frac{E}{\sum A(j)} \tag{39}$$

TABLE III
EER CALCULATION PARAMETERS [36]

Type	Class	% of utilization for energy measurement u1, u2, u3	Weight multipliers
Routing equipment	Access router	0, 10, 100	a=0.1, b=0.8, c=0.1
	Edge router	0, 10, 100	
	Core router	0, 30, 100	
Ethernet switching equipment	Access	0, 10, 100	
	High speed access	0, 10, 100	
	Distribution/ aggregation	0, 10, 100	
	Core	0, 30, 100	
	Data center	0, 30, 100	

Parker *et al.* [50] cite ECR, TEER, and TEEER but note that they do not capture all the properties of a system [51]. To solve the problem, the authors propose an absolute energy efficiency metric, $dB\varepsilon$. This metric could be applied to a system, equipment, or a component; and it introduces the temperature as an aspect of the measurement of the absolute energy efficiency. Equation 40 describes the metric. In this equation, k_B is the Boltzmann constant $1.381 * 10^{-23} J/K$, and T is the absolute temperature of the mechanism in Kelvin.

$$dB\varepsilon = 10log_{10}(\frac{Power/BitRate}{k_B Tln2}) \tag{40}$$

In the technical report “TR 103 117” (“Principles for Mobile Network level energy efficiency”) [11], ETSI lists metrics related to throughput, coverage area, and number of users. Then they propose an energy efficiency metric related to simultaneously scheduled users ε_{SS} as described in (41). In this equation, $card(U)$ is defined as the cardinality of set U, and U_{QoS} is the set of users with a given minimum QoS in the area of measurements represented by a d_{BS} number of nodes.

$$\varepsilon_{SS} = \frac{card(U_{QoS})}{\sum_{i \in d_{BS}} P_{BS,i}} \tag{41}$$

As a way to better characterize the energy efficiency of carrier IP networking equipment, Ericsson proposed to measure the Power per Subscriber and the Power per Circuit [12]. The latter can be considered for point-to-point (Virtual Leased Line) Ethernet-Line services or for multi-point (MAC Address). [9] calls them WattsPerVLL and WattsPerMAC.

E. Component-level Metrics

The authors of GreenSONAR [52] propose a metric extending the absolute energy efficiency, now calculated per port, as described in (42). They include the number of ports N_{ports} and distribute the current energy consumption P_{total} among them. The value P_{total} is correlated to the bandwidth remaining $Speed_{max} - Util_p * Speed_{max}$. As an example, the authors observe that if a port has a utilization of 80%, the metric calculates to 20% of the $Speed_{max}$ of that port in $bits/second$ ratio.

$$dB\varepsilon_{cpp} = 10log_{10}\left(\frac{\frac{P_{total}}{N_{ports}}/Util_p * Speed_{max}}{kTln2}\right) \tag{42}$$

where $dB\varepsilon$ is the absolute energy efficiency; $dB\varepsilon_{cpp}$ is the absolute energy efficiency per port; P_{total} is the total energy consumption of device; N_{ports} is the number of ports; $Speed_{max}$ is the maximum speed of port (bits/second); $Util_p$ is the port utilization; k is the Boltzmann constant ($1.381*10^{23}$ Joules per Kevin); T is the temperature in Kelvin; $kTln2$ is the absolute minimum energy dissipated per bit.

For radio resources, [53] explored bandwidth efficiency $b/s/Hz$ and power efficiency $b/s/Hz/W$ to analyze wireless links. The authors state that many researchers use these metrics. They also define the $(b*m)/s/Hz/W$ green efficiency as described in (43). In this equation, d denotes the transmitter-receiver distance, γ_s is the average Signal-to-Noise Ratio (SNR), and P_t is the transmitted power in W.

$$\eta_m = power\ efficiency * d = \frac{d * log_2(1 + \gamma_s)}{P_t} \tag{43}$$

Chen *et al.* [16] explore wireless networks' energy efficiency. An antenna efficiency can be defined by the radiated power divided by the input power to feed the antenna, as described in (44). It is also possible to talk about antenna gain. Another concern in this area is the power amplifier, the main source of power consumption. Its efficiency is defined as the ratio between the sufficient output power and the input power, as in (45).

$$\eta_{Ant} = \frac{P_{radiated}}{P_{input}} \tag{44}$$

$$\eta_{PA} = \frac{P_{output}}{P_{input}} \tag{45}$$

For the component scope, the EARTH Project cite power amplifier efficiency and also discusses the energy efficiency of transceiver systems as the ratio between the power of the transceiver system itself and the total supply power. The efficiency of the power amplifiers and the transceivers relies heavily on the level of the transmitted signal; the maximum efficiency occurs when they operate at full capacity. So, to adequately assess the performance, it is suggested to get power information at the maximum signal load and at the constant load (constant signal level) by using the Power Efficiency at variable Load ($PEvL$), as described in (46).

$$PEvL = \frac{\int_0^T P_{RFout}(t)dt}{\int_0^T P_{DC}(t)dt} \tag{46}$$

In the technical specification “TS 102 706” [32], ETSI defines two types of measurement: static, in which the measurement is done with different radio resource configurations; and dynamic, in which the power consumption is measured considering different activity levels and path losses. The specification determines the measurement conditions, including reference parameters and load level for various types of systems, such as GSM and WiMAX. Equation 47 describes the static formula to calculate the power consumption of integrated (close to each other) RBS equipment. For the dynamic type, the power consumption is defined as three different activity levels: 10%, 40%, and 70% of activity.

$$P_{equipment,static} = \frac{P_{BH} * t_{BH} + P_{med} * t_{med} + P_{low} * t_{low}}{t_{BH} + t_{med} + t_{low}} \tag{47}$$

where t_{BH}, t_{med}, t_{low}, in hours, are the duration of different load levels.

In a distributed RBS scenario, an architecture “which contains radio heads (RRH) close to antenna element and a central (C) element connecting RBS to network infrastructure,” the power $P_{equipment,static}$ is calculated by adding $P_{C,static}$ to $P_{RRH,static}$. The load levels in which the measurements should be taken are similar to those in the integrated scenario. When taking the whole site into account, the specification recommends including the auxiliary equipment and cabinets. For both cases, integrated or distributed, P_{site} is given by $P_{equipment}$ multiplied by a power supply correction factor and a cooling factor (unit less), both given in their specification.

In the technical specification “TS 102 533” [30], ETSI defines Power Consumption per Line of BroadBand Equipment (P_{BBLine}) as described in (48).

$$P_{BBLine} = \frac{P_{BBEq}}{N_{subscrib-lines}} \tag{48}$$

where P_{BBEq} is the power consumption of a broadband equipment in the operator or supplier site and $N_{subscrib-lines}$ is the maximum number of subscriber lines.

F. Discussion

There are other works that do not propose new metrics, but use existing ones. Wang *et al.* [54] review the research on green wireless communications in their book chapter. Among the topics covered, they list the following metrics: TEEER, TEER, ECR. Suarez *et al.* [55] did an overview and classification of green wireless networks in which they listed the following networking metrics: power amplifier efficiency, ECR, power efficiency and green efficiency for radio links, and coverage for urban and rural areas. Nasimi *et al.* [56] have also explored energy efficiency for wireless, but they focus on heterogeneous networks (HetNets). They cite ECG, ECR, the area power consumption. Their work uses power and energy information to evaluate energy savings made possible by using HetNets. They also apply ECG in a different way: besides the usual operational way of calculating ECG, they mention using ECG considering the embodied energy. The Smart City Cluster Collaboration [57] presents an extensive list of datacenter metrics, including Carbon Intensity, the ones from GreenGrid[2], power density (W/ft^2), SWaP, ITEU, ITEE, the ETSI KPIs, and others related to productivity, utilization ratio, grid efficiency, as well as other metrics related to cooling, UPS, lighting, building, SLA, and financial performance.

Two previous surveys [8] [9] provide partial evidence of a list of metrics related to energy and GHG emissions assessment. There was no consensus over their usage at the time of their studies, as there is still no consensus for networks or distributed clouds. There is even redundancy among metrics, with some representing essentially the same information or varying only the scale (e.g., logarithmic). According to Bianzino *et al.* [8], this can lead to “an inorganic set of unpopular, heterogeneous and non-comparable metrics,” and having an agreement on which set to use could promote comparative studies and facilitate decision processes.

These two previous surveys, [8] and [9], listed some of the metrics we have presented here, following different classifications, which were used as reference. Bianzino *et al.* [8] classified the metrics on four different levels: (1) country-level (broad indexes, like the Environmental Performance Index and the Happy Planet Index); (2) corporate-level (the authors cite ISO/TC 207 and the GHG Protocol, which are actually guidelines, not metrics); (3) facility-level (PUE, DCiE, W/ft^2, and DCP); (4) equipment-level (ECR, EER, ECRW, EPI, Power Per User, TEER, TEEER, CCR, Watts per circuit, and Watts per MAC). Wang et al.’s [9] work focused on wireless and provided a list of green metrics divided by infrastructure targets: (1) data center (PUE, DCiE, and DCP); (2) enterprises (ECR, ECRW); (3) equipment (TEER, TEEER, CCR, EPI, $P_B BLine$, and NPC); (4) IP Networks (WattsPerVLL, WattsPerMAC). With a smaller list of metrics, and focusing on the works of standardization bodies, Hamdoun et al. [45] list the following metrics: ECR and ECR-based metrics, EER, $TEER$, $EE_{coverage}$, $EE_{capacity}$, $Power\ per\ subscriber$, NPC, and ERG. Many advances and proposals have occurred since these surveys were published, both from the technological point of view and in the metrics themselves.

Table V summarizes all the metrics presented in this section divided by the scope defined in Section II and showing that, despite the lack of consensus(with the exception of the GreenGrid agreed list of metrics for datacenters [58]), some works do suggest/recommend similar metrics. Many metrics are quite close to each other, sometimes involving just a name change. Starting an standardization effort from this list could be a beginning of moving towards the definition of a common set of metrics for sustainable distributed clouds. Some institutions have already been working together on the definitions (*e.g.*, ITU-T L.1330 equivalent to ETSI ES 203 228, or ISO SC 39 working with ITU, ETSI, and Green Grid), revealing a substantial effort towards alignment.

PUE, ECR and the TEER families are the most popular metrics. These metrics are important for hardware manu-

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[2] This work presents a more extensive list of metrics from GreenGrid that are not listed in [22], probably due to the agreement reached after this work was published, as can be seen in [58]

facturers and are complemented by those that account for dynamic network conditions (*e.g.*, full-load, half-load and idle). They are also used by many other works on energy monitoring and optimization, such as PUE in [59] and [60]. It is also possible to note a significant "movement" around wireless energy efficiency metrics around 2010-2011. As is well known, for wireless, energy efficiency requirements go beyond economic and environmental reasons; it is a matter of equipment survivability owing to the reliance on batteries of the end user devices.

Metrics related to GHG emissions are fewer, and for other resources, such as water, even less. Among previous surveys, [8] cites only the GHG Protocol, applicable for corporate reporting but not actually a metric proposal in itself; and in [9] there is no mention of carbon-related metrics. Such emissions information at distinct levels could support different decision-making processes, such as virtual nodes migration decisions [61] or even routing decisions. The migrations consider carbon emissions in different regions to decide where to place the virtual nodes (in a cloud scenario). For that kind of decision, as well as corporate reporting, it could be argued that the current metrics are a good start to establish a common evaluation framework.

1) Metrics Components: One interesting aspect to note is that the vast majority of the metrics consist of the following pieces: a performance part (throughput or coverage), a power/energy information part, and an emissions component, if any. Some of them, to account for variable conditions, have these same pieces evaluated under different load conditions, but the nature of the components of the equation are the same. The main exceptions are the metrics related to users or number of subscribers, which demand such additional information.

Bolla *et al.* [62] acknowledged the common presence of throughput and power consumption components when comparing ECR and TEER, and also pointed out that, using only throughput as the performance metric may not fully characterize a device behavior. A time component is also important, mainly because some energy efficiency features increase the delay aspect, which may break QoS requirements when trying to save energy. As an example, this is the case for services migration in distributed cloud infrastructures.

2) Metrics and the New Technologies: Given the dates of publication of the previous surveys, none of them considered the developments in the ICT area, such as Software-Defined Networks (SDN), Network Function Virtualization (NFV), and architectural changes such as fog/edge computing, ICN (Information-Centric Networking), CORD (Central Office Re-architected as a Datacenter), and IoT underlying infrastructure. In light of these new areas, the CO (Central Office), cloudlets, and remote data center facilities can directly benefit from the data center metrics (even more with the current CORD trend), since all are in fact facilities (like any other networking facility). Virtual machines have some models that could benefit, for instance, the NFV middle-boxes evaluation. ICN already has its metrics, recently proposed and listed in this work.

As large numbers of switches and routers become software networks functions executed on cloud infrastructure, traditional per-linecard and per-port metrics as well as associated measuring tools need to be revisited. Dynamic dependencies on the underlying compute hardware and execution environment need to be taken onto consideration. Also, automatic update strategies that dynamically trigger metric recalculation to reflect the current execution location should be devised.

The IoT supporting infrastructure still lacks sustainability metrics considering the work to date. For instance, [63] surveys on energy conserving issues and solutions using different radio access technologies for IoT classified prior work regarding different aspects, including "metric"; however, the metrics are defined as "energy efficiency" only. The remaining challenge is how to measure and compare energy efficiency considering heterogeneous devices, new protocols, and technologies. As many of the metrics designed for traffic measurement can be applied to IoT networks [64], the same can be evaluated for energy efficiency and emissions metrics. Parameters for these metrics can be obtained through technologies such as LoRa/LoRaWAN [65], which allows communication over long distances with minimal energy consumption. Defining a set of metrics for evaluating IoT from an end-to-end perspective is important. Some existing works point out the importance of energy efficiency in this field but without actually defining how to measure this energy efficiency.

It is important to be aware that metrics technology-dependence can make it difficult to coalesce them. [8] cites a good example in this regard: "while power per subscriber and power-per-port fit well the case of a single-purpose PSTN network, Internet Service Providers (ISPs) providing triple-play services would find these conventional energy metrics insufficient for accurate evaluations."

IV. MEASUREMENT METHODS AND MEASUREMENT TOOLS

The distributed clouds energy management task relies on methods and tools to obtain, report, and analyze a system's performance and efficiency with the object of the enforcement of energy saving features. Functions for measuring and monitoring include identifying energy-managed devices and their components, as well as monitoring their performance statistics and power states [69]. By themselves, these functions do not reduce the energy needed to run a device or component. In fact, they may even increase it slightly because monitoring instrumentation also demands energy [70], whether it is through additional hardware capable of obtaining energy information, or a method implemented in software to calculate energy information based on performance indicators and models. Figure 3 illustrates the different scopes of tools/frameworks for measuring and monitoring energy efficiency.

- **Corporate frameworks**: frameworks and best-practice guidelines to promote energy efficiency and sustainability goals at the business level.
- **Facility frameworks**: interact with monitoring frameworks of different resources (network, compute, storage) in order to calculate energy efficiency at the facility level.
- **Network frameworks**: comprise a set of network nodes and servers running networking services (*e.g.*, VNFs). Energy measurement methods for networks include obtaining the energy consumption information by querying

TABLE V
METRICS SUMMARY

Scope	Metric Family	Description	Who Suggested	Also Cited in
Corporate	*Carbon Intensity*	$CO\_2e/Terabyte$	[18]	[19]
	DSE	Digital Service Efficiency	[20]	[21]
Facility	DCP / $DCeP$	Data Center energy Productivity	[22]	[21]
	PUE / $NPUE$	Power Usage Effectiveness / Network Power Usage Effectiveness	[22] (PUE) [23] (NPUE)	[21] [8] [9] [28] [57]
	$DCiE$	Data Center infrastructure Efficiency	[22]	[8] [9] [28] [57]
	GEC / REF	Green Energy Coefficient / Renewable Energy Factor	[22] (GEC)	[21] (REF) [57]
	ERF	Energy Reuse Factor	[22]	[21][57]
	CUE	Carbon Usage Effectiveness	[22]	[57]
	$ITEE$	IT Equipment Energy Efficiency for Servers	[21]	[57]
	$ITEU$	IT Equipment for Utilization of Servers	[21]	[57]
	W/ft^2	Watts per square feet considering the total computer room power density (ICT equipment plus supporting equipment)	[25]	[8][57]
	$SWaP$	Space, Watts, and Performance	[26]	[57]
	ω	Water Usage Energy Metric	[27]	-
	DC_{EM}	Global KPI of Dataprocessing and Communications Energy Management	[29]	[57]
Network	NPC	Normalized Power Consumption	[30] (ETSI)	[9] [45]
	ECG	Energy Consumption Gain	[31]	[45][55][56] [66]
	$EE_{capacity}$	Coverage of the network in a urban area	[32]	[16][45][55] [28]
	$EE_{coverage}$/ EE_{CoA}	Coverage of the network in a rural area	[34] [36]	[16][45][55] [28]
	EE_{mn}	Mobile Network data Energy Efficiency	[36]	-
	Power per Area	Power per Area Unit in W/m^2	[37]	[28][56]
	Energy Consumption	Total energy consumption (J) of ICN	[38]	-
	Network energy per bit	in J/bit in ICN	[38]	-
	ESR	Energy Saving Rate in ICN	[38]	-
	EDP	Energy-Delay Product in ICN	[39]	[38]
Equipment	ECR $NECR$ $CNEE$	Energy Consumption Rating / Network Energy Consumption Rate / Communication Network Energy Efficiency	[40](ECR)	[44] (NECR) [23] (CNEE) [8] [9] [51] [16] [54] [45] [55] [62] [56] [67]
	$ECRW$	Energy Consumption Rating Weighted	[40]	[8][9][51] [62]
	EPI $NEPI$	Energy Proportionality Index / Network Energy Proportionality Index	[43] (EPI)[44] (NEPI)	[8][9]
	EPC	Energy Proportionality Coefficient	[23]	-
	$TEER$ $EEER$ EER $TEEER$	Telecommunications Energy Efficiency Ratio Equipment Energy Efficiency Ratio Energy Efficiency Ratio Telecommunication Equipment Energy Efficiency Rating	[45](TEER) [46](EEER) [36](EER) [47](TEEER)	[8][9][51] [54][45][28] [62]
	CCR	Consumer Consumption Rating	[49]	[8][9]
	$dB\varepsilon$	Energy efficiency metric for simultaneous scheduled users	[11]	-
	$WattsPerVLL$	Power per Subscriber	[12]	[8][9]
	Power Per User / Subscriber	Power Consumption per User / Subscriber in W	[28] [68]	[8][45][11] [33]
	$WattsPerMAC$	Power per Circuit	[12]	[8][9]
Component	P_{BB_Line}	Power Consumption per Line of BroadBand Equipment	[30]	[9]
	$dB\varepsilon_{cpp}$	Absolute energy efficiency per port	[52]	-
	$b/s/Hz$	Bandwidth efficiency of a wireless link	[53]	[67]
	$b/s/Hz/W$	Power efficiency of a wireless link	[53]	[67]
	$(b*m)/s/Hz/W$	Green efficiency of a wireless link	[53]	[67]
	η_m	Green efficiency of a wireless link	[53]	[55][67]
	η_{Ant}	Antenna efficiency	[16]	-
	η_{PA}	Power amplifier efficiency	[16]	[55][28]
	$PEvL$	Power Efficiency at variable Load	[28]	-
	$P_{equipment}$	Power for Radio Base Station (RBS)	[32]	-

performance statistics and using power models or querying directly energy information when available on the nodes.

- **Network equipment**: operates as switches or routers to exchange data in a network. Energy measurement at the node includes energy measurements at the interfaces and other components. Also, comprises virtual instances of switches and machines in order to support Virtual Network Functions (VNF).
- **Component**: provide information about energy and performance from the modules of the equipment that enable communication via various media, such as copper, optical fibers and air. For the methods and tools review, we considered the component scope together with the equipment scope; for it is, in general, the equipment that reports the energy metrics, aggregating its components. But we are going to keep it as a separate scope because we believe it will gain importance with IoT and the VNFs.

Also, different techniques for designing and implementing these tools and methods can be used for categorization purposes, such as software or hardware-based measurements and non-invasive tools. Dudkowski and Samdanis [71] summarize the instrumentation and measurement techniques in Figure 4.

- **Instrumentation**: technique used for calculating/obtaining energy efficiency information:
  - **Software-based**: dedicated software agents on the measured device.

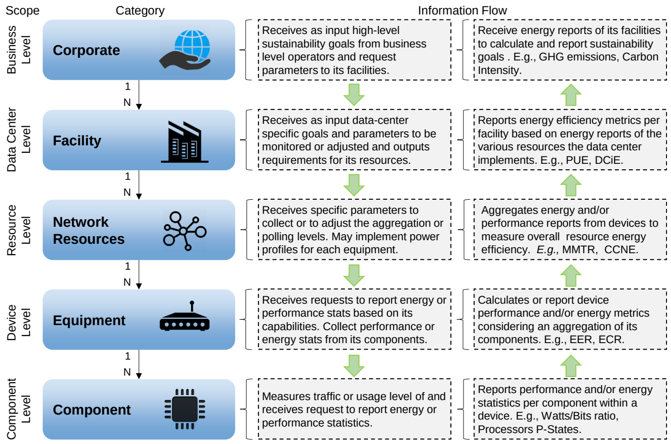

Fig. 3. Architectural scope of monitoring and measurement methods and tools

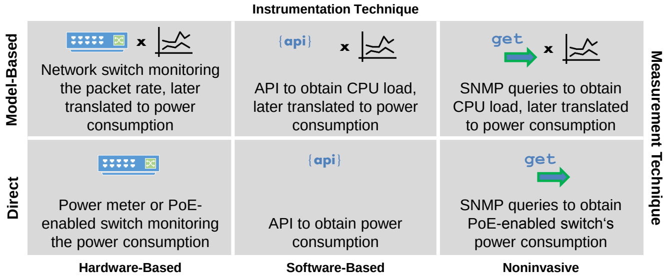

Fig. 4. Matrix of instrumentation and measurement techniques [71]

  - **Hardware-based**: dedicated physical devices to access energy parameters of the measured device.
  - **Noninvasive**: methods that do not interfere with the measured device but make use of existing support.
- **Measurement technique**: approach used for measuring energy efficiency:
  - **Model-based**: techniques that use models to measure performance parameters and in a second step translate these models into energy parameters by means of device-specific energy consumption (*e.g.*, by using power profiles).
  - **Direct**: techniques that obtain energy metrics directly.

A. *Measurement Methods*

Measurement methods comprise the processes of collection and aggregation of parameters and indicators to calculate a metric or a KPI. They influence the measurement process by determining when (*i.e.*, time interval) and how (*i.e.*, granularity) a set of parameters must be collected and aggregated for the calculation. The factors when and how influence the choice of a tool implementing the necessary type of instrumentation and measurement technique to collect and aggregate parameters. Measurement methods are not considered as tools because they do not actually retrieve energy information or deploy energy profiles, as recommended by IETF [69]; but they can support such capabilities, planning activities, or even become a complete tool in case they are implemented. It is also important to note that the methods presented herein are not the ones that specify the exact parameters for the equipment measurements to take place (*e.g.*, the room temperature or the size of the packets), but the methods that provide information and/or can result in implemented tools for obtaining and processing sustainability-oriented data.

1) Corporate-Level Methods: Comprise high-level KPIs and metrics, mainly with reporting, less so with technical purposes. ISO 14064, a standard on how to measure Green-House Gas (GHG) emissions, was the basis for the Carbon Measurement Protocol proposed in the GreenStar Network project [72] and released by the Canadian Standards Association under the name “ICT Greenhouse Gas Reduction Project Protocol: Quantification and Reporting” [73]. The scope of this protocol is to quantify the emission reductions as a result of moving services to low carbon environments or improving energy efficiency.

Another well-known publication in this scope is the GHG Protocol, which contains guidelines for accounting and reporting GHG emissions, directly or indirectly caused by a company [17]. To be able to calculate the metrics related to GHG emissions, it is paramount to have accurate emission factors (in gCO_2e/Wh). The emission factors are then put together with energy information (in Wh) to calculate a number of emissions (in gCO_2e). Electricity is a significant contributor to emissions in the telecommunications industry. The information regarding energy and emissions is in general calculated per facility, later aggregated for reporting purposes or for management systems which later decide on the basis of the data obtained (*e.g.*, decisions about Virtual Machines migration according to the emissions in the geographically distributed sites).

For organizations, ITU-T has the ITU-T L.1420 [74], a methodology for assessing energy and GreenHouse Gases (GHG) emissions of ICT, based on ISO 14064 and on the GHG Protocol. It can be used as a supplement for both. It is part of ITU-T L.1400 [75], which brings an overview for accessing environmental impacts of ICT. As the GHG Protocol, it considers direct, indirect, and other indirect emissions and covers how to design and develop an inventory, which components should be considered, quality management requirements and reporting of the inventory results. ITU also has ITU-T L.1430 for projects [76], and ITU-T L.1440 for cities [77].

2) Facility-Level Methods: Describe approaches towards efficient energy and emissions management of a whole site. As mentioned in the previous sub-section, emission factors information is required to calculate total emissions. When it comes to emissions due to the electricity demand, companies have been promoting the use of renewables locally to power their facilities. In cases in which the site is completely powered locally, the calculation of the emission factors resorts to the weighted sum of the different sources’ emission factors [72]. But even in this case, the electricity grid may be used as a backup power.

The evaluation of electricity grid emission factors is challenging [78]. Maurice *et al.* [79] developed a temporally differentiated Life Cycle Assessment (LCA) model to calculate carbon emissions related to electricity generation. The model was a response to the usual approach based on fixed coefficients, which neither reflects the variability observed in the electricity system nor takes the location into account. Their proposal is described in (49).

$$\begin{aligned} &Carbon\ Footprint\ (kgCO_2e) = \\ &\sum_i electricity\_source_i(\%) * \\ &electricity\_consumption(kWh) * \\ &emission\_factor(\frac{kgCO_2e}{kWh}) \end{aligned} \tag{49}$$

In general, data about energy generation, local demand, imports, and exports can be obtained from operator's websites. And for regions that do not disclose this information or do not have the divisions on the required granularity, it might be possible to estimate using historical and neighbor regions' information, depending on the data available and with a certain degree of uncertainty. Riekstin *et al.* [60] proposed a research framework to support green metrics (*e.g.*, PUE, GHG emissions) for geographically distributed ICT facilities (or services) which supports the collection and calculation of emission factors considering temporally differentiated data from the distributed facilities. Upcoming big data approaches, which can help the operators in producing energy in a more efficient way [80], may also play an important role in providing information for the GHG calculation methods and consequent actions planning and execution.

ITU-T L.1410 [81] is a guide to ISO 14040 and ISO 14044 for a complete Life Cycle Assessment (LCA) of ICT networks, products, and services. ETSI has the technical specification "TS 203 199" [82] equivalent in technical content to ITU-T L.1410. In this work, we classify this guide as a facility method because the document says that ICT networks and services "can be seen as logical structures", composed by ICT goods and all supporting infrastructure, including building premises and supporting infrastructure.

3) Network-Level Methods: [68] defined a method to estimate the energy consumption of access (ADSL, PON, FTTN, and PtP), metro, edge, core and video distribution IP optical networks. The authors studied the consumption per customer and per bit of data transported in the Internet. They also took into account over-subscription and the possible improvement rate of energy efficiency with technological advances. Then, they obtained specific information from manufacturer data sheets and included estimated overheads (e.g. for cooling). Equations [50-55] describe the power consumption as calculated in their work.

$$P_{access} = P_{CPE} + \frac{P_{RN}}{N_{RN}} + \frac{2P_{TU}}{N_{TU}} \tag{50}$$

$$P_{metro} = 2\left(P_{ES} + 2A_I\left(\frac{\widetilde{P}_{Gateway}}{C_{Gateway}} + \frac{\widetilde{P}_{PEdge}}{C_{PEdge}}\right)\right) \tag{51}$$

$$P_{VDN} = 4 * \frac{3A_C}{120Gbps} * 4.6kW \tag{52}$$

$$P_{core} = \frac{8A_I(H+1)}{640Gbps} * 10.9kW \tag{53}$$

$$P_{link\_core\_terrest} = 4\left(\frac{A_I(1-U)}{40Gbps}\right) * \frac{H}{2} * 235W \tag{54}$$

$$P_{link\_undersea} = 4\left(\frac{A_I U)}{10Gbps}\right) * H * 280W \tag{55}$$

where the factors of 2, 4 or 8 account for overheads from redundancies, over-provisioning, external power supplies or cooling, among others; the factor of 3 "is included because three routers are transited for two hops"; N_{RN} is the number of customers who share a remote node; N_{TU} is the number of customers who share a terminal unit; P_{CPE} is the power consumed by the Customer Premises Equipment; P_{RN} is the power consumed by the Remote Node at the central office; P_{TU} is the power consumed by the Terminal Unit at the central office; P_{ES} represents per-customer power consumption of the edge Ethernet switches; $\widetilde{P}_{Gateway}$ is the total power consumption of a gateway router; $\widetilde{P}_{PEdge}$ is the total power consumption of a provider edge router; $C_{Gateway}$ represents the capacity of the gateway routers; C_{PEdge} is the capacity of the provider edge routers; A_I is the current per-customer public Internet capacity assumed as 100 Kpbs (in 2009); H is the number of core node hops; U is the "the proportion of traffic going to neighboring nodes through undersea WDM systems"; the figures of 235W and 280W are the cumulative power per channel (2009).

In a subsequent work [83], the same authors focused on the access part, including wireless networks. Access networks can be divided in three components: customer premises equipment, the remote node or base station, and the terminal unit (inside the local exchange/central office). The equation is the same as the P_{access} in (50). Using data sheets, the authors created Table VI with the parameters they later used to estimate the total energy consumption at present and in the future. To estimate future energy consumption, they considered the following "per-annum business as usual improvements rates":

- Electronics: 26%;
- Optical interfaces: 5%;
- Power conversion: 0%;
- Power amplifiers: 0%.

TABLE VI
PARAMETERS USED BY [83] FOR ACCESS NETWORKS EQUIPMENT

	P_{TU} (W)	N_{TU}	P_{RN} (W)	N_{RN}	P_{CPE} (W)	Tech. limit (Mbps)	Per-user capacity (Mbps)
ADSL	1.7	1008	N/A	N/A	5	15	2
HFC	0.62	480	571	120	6.5	100	0.3
PON	1.34	1024	0	32	5	2.4	16
FTTN	0.47	1792	47	16	10	50	2
PtP	0.47	110	N/A	N/!	4	1	55
WiMAX	0.47	24400	1330	420	5	22	0.25
UMTS	0.47	15300	1500	264	2	20	0.25

4) Equipment- and Component-Level Methods: Hinton *et al.* [84] state that the power model depends on how the equipment is shared. For access equipment shared among a few users (lightly shared), a "time-based" or a "power per user" model is adopted. For edge and core equipment, shared among many users (highly shared), a "capacity-based" model is typically adopted. Such a schema is generally used for Ethernet switches that aggregate traffic in metro/edge networks, the gateways and edge routers in the metro, and optical links in the core. Equation 56 describes the power per user model for lightly shared equipment that is continuously powered. When the equipment has intermittent access, a time-based, more complex model, is necessary. For edge and core equipment, highly shared, the authors propose (57).

$$P_{user,Access} = P_{CPE} + X_{RN}\frac{P_{RN}}{N_{RN}} + X_{TU}\frac{P_{TU}}{N_{TU}} \tag{56}$$

where P_{CPE} is the power consumed by the Customer Premises Equipment; P_{RN} is the power consumed by the Remote Node; P_{TU} is the power consumed by the Terminal Unit; N_{RN} is the number of customers who share a remote node; N_{TU} is the number of customers who share a terminal unit; X_{RN} and X_{TU} are the additional power required, and may be expressed as the PUE, for example.

$$\begin{aligned} P_{Edge+Core} = C_{Peak}\frac{M_{edge}}{\rho_{E,max}}(\frac{\langle P_{idle,E}\rangle}{\langle C_{E,max}\rangle} + \rho_{E,op}\langle E_E\rangle \quad (57)\\ +\alpha(\frac{\langle P_{idle,C}\rangle}{\langle C_{C,max}\rangle} + \rho_{C,op}\langle E_C\rangle)) \end{aligned}$$

where C is the capacity in bps, and $C_{E/C,max}$ is the maximum capacity of the given Edge/Core router; E is the energy consumption; M represents the number of equipment; P is the power; ρ is the utilization as a fraction of time.

IETF (Internet Engineering Task Force) proposed the EMAN (Energy Management Framework) in RFC 7326 [41] for energy management of devices and their components within or connected to communication networks. The RFC 7326 defines a reference and an information models consisting of, respectively, energy management domains and energy objects. In traditional SNMP-based energy management systems, the power consumption of a device is measured by the device itself. However, EMAN takes a different approach, in which the device energy consumption is reported by a different system. Each energy management domain comprises one or more energy objects (which are MIBs explicitly defined to report energy statistics). For instance, each energy object managed by an energy management domain can be monitored and controlled on its power state, power attributes, battery.

The Green Abstraction Layer (GAL) [85] has been proposed; it adds the performance for each possible energy-aware state (EAS) besides hiding the devices and components architectural complexity. GAL defines a set of abstract data objects (known as energy-aware states) that describe the power management settings of energy management capabilities available on network nodes and at the network level itself. It acts as an interface between data and control planes for exchanging data regarding the power status of a device intended for SDN environments. It was conceived so as to enable the control processes to acquire information on the capabilities available on the data plane, configure them, and report energy consumption [85].

At the equipment level, getting information for virtual instances relies on mathematical approaches. Estimating the energy consumption of virtual machines (VM) is a big challenge in optimizing energy consumption. In this sense, understanding the influence of a virtual node on the network infrastructure is also important. Some studies have focused on estimating and profiling energy consumption at the VM level and its virtual resources. For instance, Krishnan *et al.* [86] explored the feasibility and challenges in developing methods for black-box monitoring of a VMs power usage at runtime, on shared virtualized compute platforms

Carbon assessment on virtualized infrastructures is becoming increasingly important [87]. In their work with the GreenStar network, Moghaddam *et al.* [88] defined an energy and carbon measurement model for Virtual Machines (VMs) in a geographically distributed cloud environment. Equation 58 describes the model for energy consumption.

$$\begin{aligned} E(t,\Delta T) = E^{(S)}(t,\Delta T) + E^{(N)}(t,\Delta T) + \\ E^{(R)}(t,\Delta T) + E^{(M)}(t,\Delta T) + \\ E^{(U)}(t,\Delta T) + E^{(F)}(t,\Delta T) \end{aligned} \tag{58}$$

where $E^{(S)}$ represents the server's energy consumption; $E^{(N)}$ is the energy consumption of the network devices; $E^{(R)}$ is the energy consumption of the storage devices; $E^{(M)}$ represents the migrations energy consumption; $E^{(U)}$ is calculated on the basis of energy consumption readings from PDU (Power Distribution Unit) devices; and $E^{(F)}$ represents the energy demanded by the switch on/off events.

5) Discussion: As for the metrics, besides the existing standards for energy efficiency such as the Energy Star [89], there is no consensus on which methods to use in order to measure and report energy consumption [90]. Table VII summarizes the methods presented in this Section. Some of these methods do not have specific instrumentation or measurement techniques because they are not acting/working directly with the equipment or components. As for the equipment, most of the methods are non-invasive and model-based, reflecting the nature of the works. The existing methods to estimate energy, despite not being readily available/implemented, are good tools for understanding the infrastructure and its parts and relationships, as well as for network planning. And, of course, they provide a good basis for the implementation or improvement of tools. The fact that they are mostly non-invasive may also be an advantage. The same applies for the methods which target virtual infrastructures.

For IoT, Martinez *et al.* [91] present a model for the sensor nodes, defined in their work as the backbone of IoT. Something that could be done is to expand the work by taking into account an end-to-end approach, not only the sensor nodes, but also comprising GHG emissions that might be different according to the location of the node.

The GHG accounting methods are gaining momentum. But, in general, they use average emission factors for reporting. To be more accurate, the temporally differentiated LCA is a promising approach, despite being heavily dependent on the availability of the information. IEEE has an ongoing

TABLE VII
MEASURING AND MONITORING METHODS SUMMARY

Scope	Measuring Method	Description	Instrumentation	Measurement Technique
Corporate	Carbon Measurement Protocol [72]	Protocol to quantify the emission reductions due to moving services to low carbon environments or improving energy efficiency, based on ISO 14064	N/A	N/A
	GHG Protocol [17]	Guidelines for accounting and reporting GHG emissions, directly or indirectly caused by the company	N/A	N/A
	ITU-T L.1420 [74]	Methodology for assessing energy and GHG emissions of ICT in organizations	N/A	N/A
Facility	Temporally differentiated LCA [79]	To calculate carbon emissions related to electricity generation	N/A	N/A
	ITU-T L.1410 [81] and ETSI TS 2030199 [82]	Guide for LCA assessment of ICT services, networks, and products	N/A	N/A
Network	Baliga *et al* [68]	Method to estimate the energy consumption of access (ADSL, PON, FTTN, and PtP), metro, edge, core and video distribution IP optical networks	N/A	N/A
	Baliga *et al.* [83]	Method to estimate the energy consumption of access networks, including wireless	N/A	N/A
Equipment	Hinton *et al.* [84]	Method to estimate power consumption of lightly shared (e.g., customer equipment) or highly shared equipment (e.g., Ethernet switches which aggregate traffic in metro/edge)	N/A	N/A
	EMAN [41]	Reference model and an information model consisting of, respectively, energy management domains and energy objects	Non-invasive	Direct
	GAL [85]	Defines a set of energy-aware states that describe the power management settings of energy management capabilities available	Non-invasive	Model-based
	Krishnan *et al.*	Developing methods for black-box monitoring of a VM's power usage at runtime	Non-invasive	Model-based
	Moghaddam *et al.* [88]	Energy measurement model based on the resource usage and performance counters to obtain carbon emissions values from VMs	Software-based	Model-based

standardization effort which is currently developing a method for calculating emission factors in a more accurate way using temporally differentiated LCA [92].

B. Measurement Tools

Tools are physical devices or logical components that implement one or more measurement methods or metrics/KPIs to gauge energy consumption in networks. According to IETF [69], tools are defined as capable of monitoring and measuring energy consumption in networks if they fulfill at least one of the two approaches:

i) retrieve energy information: collect information related to power states (*e.g.*, current state, time to transit between states), and/or energy consumption (*e.g.*, total energy consumption, total energy consumption per power state). The instrumentation is in general hardware-based or noninvasive, and the measurement technique, direct.

ii) deploy energy profiles: network frameworks or devices that do not retrieve energy consumption information, but calculate it based on performance counters and energy profiles. The instrumentation is in general software-based, and the measurement technique, model-based.

Other recommendations by RFC 6988 [69] and ITU-T Y.3022 [93] were defined to guarantee that the operation of energy measurement and the monitoring tools run with the minimal amount of overhead possible and support the different metrics and KPIs. These recommendations and [94] are consolidated into the following list and are also used to evaluate the surveyed solutions:

1) **Support real-time energy measurements** [60]: tools should perform real-time measurements taking into account the instant ratio between usage and supplied power to a device if energy information is available, or retrieving the supplied energy information from a PDU (Power Distribution Unit) to calculate the ratio with performance counters.
2) **Measure according to the traffic load** [93]: it is recommended to measure energy information according to traffic load, which is dependent on Equipment and Component-level power states. Also, effects of the overhead on traffic engineering should be included since overhead has an impact on energy consumption.
3) **Enable different granularities of monitoring control** [69], [60], [95]: the monitoring should be ideally performed on a finer granularity level than the Equipment level and be available for components of devices.
4) **Perform remote and aggregated monitoring** [69], [94]: measurements can be performed locally (which consumes energy) or remotely by a device that can aggregate the information of other devices and report the energy

consumed. Furthermore, aggregated measurements can be combined with local measurements by using nodes that can act as mid-level managers or protocol converters for several devices that measure power consumption by themselves, like a home gateway.

5) **Ensure accuracy and reliability of measurements** [69]: depending on the technique to measure energy consumption values, the confidence in the reported levels may vary. Therefore, the confidence in the reported values should be qualified and quantified on the basis of the accuracy of measurements. Furthermore, measurements should be done several times to establish confidence intervals.
6) **Support for custom metrics** [94]: since it is not feasible to previously define every metric the user might need, it is desirable to enable users of the framework to define specific metrics according certain defined constructs.
7) **Store historical data** [94]: for auditing purposes, tools should be able to store historical data, near real-time processing, scalability, and elasticity.

1) ***Corporate-level Tools:*** Corporate-level tools are designed to support business-level decisions. These tools are mainly frameworks implemented in software that can collect performance counters/indicators from one or more facilities (*e.g.*, data centers or Points-of-Presence), or deploy power models. The main goal of these tools is to support business decisions aiming to enhance sustainability levels from a global corporative perspective.

G.W.A.T.T. (Global 'What if' Analyzer of neTwork energy consumpTion) [96] is a software and model-based tool proposed by the GreenTouch consortium [97]. The goal of G.W.A.T.T. is to allow operators and industry stakeholders to understand the energy impact of different kinds of technologies and architectural evolution, such as SDN and NFV. Energy models are used to forecast how much power is consumed by these technologies, including "home and enterprise networks, wireless and fixed access networks, metro, edge, and core backbone networks and the service core and data centers." A traffic data model is used for each network geographical region and time, and a network element/technology efficiency model is used to profile energy consumption. The traffic data model is expressed in Exabytes/month according to the geographical region of interest (worldwide or regional), and it can be associated with different projections of traffic growth. Although not providing information about the used models or details on the consumption modeling of the various kinds of supported equipment and technologies, the energy consumption is calculated on the basis of information from various public data and other independent consortia, such as the Global e-Sustainability Initiative (GeSI) [98]. G.W.A.T.T. is available for public use at [99] at the time of this study and, despite being a simulated tool, it is indeed a good "what if" analyzer, as intended to be.

The Energy Efficiency Evaluation Framework (E^3F)is a proposal of the EARTH Project (Energy Aware Radio and neTwork tecHnologies) aiming to provide a view on the power consumed by Radio Access Networks (RANs). The E^3F comprises traffic and power models to describe RANs characteristics and scenarios in short and long terms. A small-scale or short-term simulation has as goal to define a reference model with parameters and scenarios ensuring comparable results. The simulation for small-scale RAN scenarios covers different deployment areas such dense urban, urban, suburban and rural. E^3F extends the short-term evaluations to a global scale by mapping reference scenarios to a country and European scale, using models and data extracted from operators. E^3F also comprises methodologies and metrics that provide a comparison between different networks' technologies and network devices. For instance, it compares a system without energy savings capabilities and a system with integrated energy savings capabilities provided in the E^3F. It also comprises statistical traffic models to extend existing small-scale frameworks to a global scale, covering countrywide geographical areas and ranging over long-term traffic patterns. The tool also accounts for the traffic load variations by time of day and week in different regions to dynamically reconfigure the network. For small-scale and short-term evaluations, the framework needs to consider a system level simulation platform. However, a specific configuration of the models (power and traffic) is necessary to meet the level of detail on the particular network device. At the time of this study, the authors were not able to find the source code or download the tool.

Another corporate-level solution is the Cloud Sustainability Dashboard [100] proposed by Hewlett-Packard (HP). It is a simulation, software and model-based, tool that seeks to quantify, assess, and understand the sustainability impact of large-scale systems. The tool is based on economic (*e.g.*, electricity prices), ecological, and social models and on data retrieving high-level data and low-level data from IT equipment (*e.g.*, performance level, power source). The dashboard proposed by the authors shows real-time metrics or interface with other tools to enable a sustainability-aware management. In the economic model, the tool estimates costs from compute, storage, network, facility, and IT support, besides energy efficiency. The ecological model includes carbon emissions, water usage (*e.g.*, WUE: Water Usage Effectiveness) and resource consumption (*e.g.*, natural gas). The social model includes an assessment of country-specific development indicators and socio-political stability data acquired from the World Bank's World Development Indicators (WDI). The tool provides in the description of the work the models used in the dashboard, but, to the best of the authors' knowledge, the dashboard is not open-source, or openly available for download.

Cisco proposes the EnergyWise [101] framework. Their tool measure and control energy consumption and utilization from different facilities using EnergyWise collectors. These collectors are deployed in the network infrastructure of a data center, gathering performance counters from devices through standard interfaces, such as SNMP and IPMI. All the collected data is sent to a management suite deployed on the cloud, which, based on modeling approach, converts performance data into parameters defined by the operator. For example, energy use, costs, savings, and carbon emissions by device, location, cost center, division, and time of day. As expected for a commercial tool, it was not openly available at the time of this study.

Energy Star, an international standard for energy efficiency, offers an energy tracking and benchmarking spreadsheet tool called Energy Tracking Tool (ETT) [89]. ETT is intended to assist small companies in tracking and monitoring energy levels, costs, and GHG emissions over a period of time. On the one hand, as a spreadsheet-based tool (and, therefore, not deployable), it requires the models' customization to calculate energy consumption, costs, and emissions metrics, as well as the input of data for these models. On the other hand, once configured, the tool offers an easy-to-use solution for small companies that need to produce energy efficiency or emissions reports. In the initial stage, for example, one would enter production measures, such as tons of product and labor hours, and these units could then be used to normalize energy and emissions to any measure of production. In the following stages, geolocation information is required to calculate GHG emissions from the purchased electricity in the region and the input of energy data. Optionally, ETT allows to set energy and GHG goals in terms of intensity or absolute reductions. At the time of this study, ETT was available for download at [102].

The Center of Expertise for Energy Efficiency in Data Centers of the U.S. Department of Energy offers other excel-based tools for understanding and improving the energy efficiency of datacenters. This set of tools is offered through the Data Center Profiler (DC Pro) Tools [103], which is an excel spreadsheet aimed to support operators for estimating metrics such as PUE and analyze how energy is being consumed within every resource, as well of the datacenter in general. The DC Pro require as input the energy profiling from resources such as cooling, compute nodes, electrical power chain, fans, as well as usage data to calculate PUE. The initial step is the profiling of each resources, which is done via several questionnaires that configures parameters used in the energy models of each resource. In the second step, the operator has to fulfill energy consumption data of each resource, which provides an overview of energy consumption per subsystem and the overall data center consumption and PUE. Besides, the DC Pro tool and all guidelines are available for download.

*2) **Facility-level Tools:*** Tools at this level are frameworks that can either implement interfaces to receive counters of performance or resource energy, or simulate the power consumption of a data center through models for each of the resources deployed. Therefore, these frameworks can use a combination of hardware and software instrumentation, or they can be purely software-based.

Energy Sensing [104] is a research proposal (and, therefore, does not seem to be openly available for download) that seeks to integrate energy counters of smart facilities, into a management tool. Energy Sensing provides an integrated communication channel to report energy consumption levels from the various resources in a facility. Thus, communications media (*e.g.*, wired, wireless), protocols, and power-line communication technologies can be used to collect data as an input to improve energy efficiency levels. Multiple applications, including in-building facilities control, HVAC (Heating, Ventilation, and Air Conditioning), lighting, fire and safety control, and building access control, can be integrated into a single communication channel. Energy Sensing also combines a hardware-based instrumentation using a direct polling to gather counters directly from resources, with a software-based instrumentation that aggregates the collected data as an input to a network management tool. The authors state that the biggest challenge is the lack of standardized interfaces between the various kinds of equipment deployed in a facility, which makes it difficult to collect information from these resources. To tackle this problem, they propose a "smart box" to enable the integration and communication of these devices. The smart box would act as an interface between existing equipment to exchange metered information among the devices.

Tenschert *et al.* [105] proposed ECO2Clouds, an academic monitoring framework to support performance-level adjustments in a cloud-based environment. The framework use a Zabbix monitoring server based on a layered model to distinguish between physical and virtualized devices. Zabbix is a software that monitors different parameters of networks, servers, and services to report availability, user experience, and quality of services. For example, the framework uses Zabbix to gather fine-grained metrics, such as carbon footprint of a VM or a physical device. Each device on the proposed framework deploys a Zabbix client agent for gathering information and sending it to the Zabbix server. To enable power measurements for the different layers, PDUs (Power Distribution Units) are attached to the physical servers using a hardware-based approach to collect power information. Then, monitored parameters are derived according to the selected metrics. The power consumption of VMs is calculated by deriving information from the infrastructure and the virtualization layers, monitoring parameters such as used memory, data I/O identified by the send and receive actions, disk activity detected in read and write operations, and consumed CPU seconds. ECO2Clouds *et al.* uses a combination of a hardware-based instrumentation and direct polling with a software-based module based on models. Thus, performance counters of physical devices and VMs are obtained in real-time through the Zabbix collectors, and models are deployed to calculate energy metrics (*e.g.*, PUE, DCeP, and Carbon Intensity) by converting performance counters. At the time of this study, this tool repository was available at [106].

An open source solution from academia to monitor energy efficiency for small and medium data centers is GreenHop [107]. It allows checking whether the specified environmental conditions are in compliance with regulations by monitoring internal climatic changes in a server room. As the ECO2Clouds tool, the GreenHop architecture also uses a Zabbix monitoring system deploying Arduino nodes as Zabbix agents and a Banana Pi (Single Board Computer such as a Raspberry Pi device) as the Zabbix server. The nodes' communication and coordination rely on the ZigBee protocol [108], which is designed for low operating power, low data rate, and low implementation cost devices. However, GreenHop has performance constraints deriving from its hardware components. Therefore, the analysis and storage of large datasets is restricted to a small number of nodes. GreenHop source code is available at [109].

To provide a general view of the energy consumption of data center infrastructure, the private company PowerAssure developed a solution termed Software-Defined Power (SDP) [110]. The SDP takes in consideration a hardware-based instrumentation combining with different measurement techniques. Data is collected via polling with real-time measurements, and models are defined to predict day-ahead pricing, power quality, and reliability forecasts. The solution relies on PAR4 measurements on the servers to forecast how much energy would be consumed by a server under a particular set of workloads. PAR4 is a system proposed by SDP to measure actual idle and peak power consumption of individual IT equipment and IT racks. On the network side, the system relies on power measurements made available through standard protocols such as SNMP and widely-used management tools such as IBM Tivoli, HP Openview and Nagios to supply data. However, to obtain energy information from SNMP-based network devices, specific MIBs for collecting energy information are required. We were not able to check SDP's source availability at the time of this study because the company website seemed to be down.

Focusing on cloud computing energy efficiency, Kwapi [111] is an open-source plugin available at [112] designed for acquiring power consumption metrics in an OpenStack-based cloud platform. It collects power information from various wattmeters in the infrastructure to interface with Ceilometer (the telemetry component of OpenStack). The Kwapi architecture is based on a layer of drivers, that retrieve measurements from wattmeters and a layer of plugins that collect and process them. Different kinds of wattmeters (IPMI - Intelligent Platform Management Interface, Eaton PDU, Wattsup, etc) are supported, and these wattmeters communicate via IP networks or serial links. The Kwapi plugin layer offers an API that can be queried by Ceilometer. Published counters are energy (cumulative) in kWh and power (gauge type) measured in watts. Kwapi can be used to monitor the overall energy used in the data center, energy efficiency scheduling, and usage-based billing. An application of the Kwapi framework was proposed by Cima *et al.* [113] to manage cloud resources with a focus on energy efficiency.

*3) **Network-level Tools**:* Network frameworks collect and aggregate counters from physical or virtualized devices. These frameworks commonly use model-based approaches to convert performance counters obtained via standard network interfaces/protocols, such as SNMP, OpenFlow, and IPMI. Also, these frameworks can obtain energy information directly from wattmeters attached to network devices or smart PDU's, providing a direct collection of energy information.

GreenSONAR [52] is a multi-domain energy profiling system based on perfSONAR [114]. Performance counters and energy information are obtained by combining hardware and software-based approaches from different sources. Per-port/interface performance counters are obtained via SNMP/MIBs and OpenFlow, while PDUs are the data source of energy information. GreenSonar was designed as a monitoring module to calculate power information and provide input to a management framework, which manages the network by considering the trade-offs between system availability and energy efficiency. The RRD and SNMP entities are used to obtain power/performance metrics from network devices. A script is employed to query information from SNMP, and RRD[3] entities. Information from these sources are stored in a measurement "MAIN-DB" and queried to calculate the metrics in the following step. The authors use power models of vendor-specific devices to calculate energy metrics, such as PUE and TEEE, in different granularities. The hardware-based approach is deployed to measure energy consumption directly from PDUs, and a software-based approach is used to calculate the energy consumption from counters obtained via SNMP/OpenFLow. At the time of this study, the authors were not able to find the source code or download the tool.

EnergyAudit [115] is a proposal from the academia to audit the power consumption in medium and large-scale network infrastructures. It comprises three components: (i) an API for interfacing with existing management infrastructures in order to ensure interoperability with existing devices (such as SNMP-based devices) and enabling devices to be queried; (ii) a benchmark database that maps device configurations and operating status to power consumption; and (iii) an auditing tool that queries an open-access database. The open database is made available for public consultation in the audit framework, enabling both community and manufacturer to contribute with power consumption estimates. It is used for storing and mapping power consumption from several types of networking devices and their configurations. Using the database, the auditing framework implements a method that matches the network configurations to the benchmark power consumption values; then a network-wide power consumption is calculated and reported in the database. At the time of this study, the source code repository of EnergyAudit was available at [116].

TrendMeter [117] is a monitoring tool developed in the context of the TREND European research project (Towards Real Energy-efficient Network Design) for monitoring the power and the utilization of network devices. The tool uses a hardware-based approach, polling directly the network nodes for performance or energy counters (if the Energy Monitoring MIB [118] is available). TrendMeter uses a centralized server to consolidate measurements from network devices to analyze similarities in patterns of power utilization by these devices. The TrendMeter architecture is composed by three main components: device back-end, server-back end, and server front-end. The device back-end is the software deployed in the target network device capable to collect energy and traffic statistics using SNMP queries or a simple *ifconfig* command. Additionally, power consumption can be measured directly using a Wattmeter. Measurements are collected by an interface gateway, that acts as a middle layer software agent implemented in a separate machine, to aggregate and average the measurements over a coarser time scale. Then, the server-back end collects these measurements over a secure channel and the raw data is converted into a structured storage to be displayed in the server front-end. At the time of this study, the authors were not able to access the tool through the link

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[3] RRDtool (Round-Robin Database tool) aims to handle time series data such as network bandwidth, temperatures, or CPU load.

in which it used to be available[4].

*4) **Equipment- and Component-level Tools:*** Comprise tools and protocols to collect counters from physical or virtualized networking devices, and provide an interface to monitoring tools at the network-level. These tools/protocols are usually standardized to interface with monitoring tools of different vendors. To this end, the IETF proposes MIBs to support the collection of information on energy efficiency in a non-intrusive way. RFC 7460 (Monitoring and Control MIB for Power and Energy) [118] was proposed in the context of EMAN detailed in Section IV-A to define standards of an MIB for use with network management protocols. It has two independent modules, one called "energy object MIB" containing tables for profiling energy metering capabilities and power consumption statistics, and other designated "power attributes MIB" focusing on power quality measurements for energy objects, as defined in RFC 7461.

The Energy Object Context MIB (RFC 7461) [119] defines a subset of RFC 7460. Among the defined characteristics are the identification of devices and their sub-components characterized by the power-related attributes, context information (*e.g.*, domain name, role, key-words), and the energy relationship between the devices, as one energy object may interact or influence the energy consumption of other energy objects. It is also described how energy information should persist in case a device is reloaded.

Joulemeter [120] is a corporate tool proposed by Microsoft Research to perform power metering at the virtual machine level. It can track resources such as CPU, disk, screen, and applications (*i.e., browser*, and estimates power usage. Drawing on existing instrumentation available on the hypervisor, the authors offer low-overhead power models to calculate power consumption at runtime by measuring usage counters of these resources and converting the resource usage, in a model-based approach, into actual power usage. However, Joulemeter do not comprise models to track power usage of network resources. Joulemeter was available for public access until 2012, when its capabilities were included in other Microsoft products.

IPMI (Intelligent Platform Management Interface) is not exactly a tool, but a standard interface promoted by Intel, Dell, HP, and NEC that can read Advanced Configuration and Power Interface (ACPI) status to monitor and manage computer systems that implement it [121]. It defines interfaces for monitoring parameters such as temperature, voltage, fans, power supplies, and chassis. Additionally, IPMI can power the assets on or off, thus facilitating the management of the physical server. The primary features of IPMI are [122]: i) supervision of the hardware by reading temperatures and voltages; ii) management of the hardware being able to shutdown/restart a server; iii) logging; and iv) providing an inventory of the hardware.

In distributed clouds, a significant portion of the networking functionality is deployed in the form of software that executes on a general-purpose compute platform. In the following paragraphs, we briefly review key basic capabilities related to energy metering in servers. Microprocessors contain increasingly complex features for controlling the power consumption. Independently modifying the frequency and voltage for cores and memory access is available for several generations of Intel chips, and the newer chips have even more features and improved control.

The Linux Intel RAPL (Running Average Power Limit) Power Meter [123], for instance, is an open-source power meter proposed by Intel that enables software power metering for CPU and DRAM. It uses the Intel RAPL proprietary interface [124], which provides actual or estimated energy and power consumption information depending on the processor version [125] through model specific registers (MSR). CPU RAPL counters were confirmed to be highly accurate [126], while the power consumption of memory was found to be less precise [127]. The RAPL power meter also uses the Linux Powercap framework (*sysfs* interface), which allows to get information, as well as to set configurations on Linux kernel 3.13 or newer. The power meter starts a small HTTP server which waits for "GET" requests to calculate power and display, allowing easy interaction.

Another well-known tool is the PAPI (Performance API), which specifies an API for accessing counters of different processors. It has an upper (API) and a lower layer, which has functions to access the machine-specific substrate. PAPI uses the most efficient and flexible of three options that may be available: the operating system, a kernel extension, or assembly functions to access the registers. If the necessary features are not available, PAPI tries to emulate them [128]. Weaver et al. [129] extended PAPI to measure and report energy and power values. It works both with external power meters (which are less likely to be used on production environments), and with internal measurements, like the ones supported by the Intel RAPL. In this case, for instance, PAPI uses the Linux "MSR driver" which, with the right permissions, allow it to access registers directly, without needing kernel support for reading power data (the control would still need to be done via Intel RAPL). We refer the reader to [130] for more information on the PAPI component that controls power and related work, as well as to [131] for other ideas on how to deal with shared hardware.

C. *Discussion*

There are other corporate level tools from companies, such as Siemens [132] and ABB [133]. These tools are energy monitoring and reporting frameworks that focus on providing insight on how energy is consumed in industrial buildings. However, these reports do not disclose any technical information describing the methods, metrics, or instrumentation used in these tools. Table VIII presents a summary of the tools surveyed in this section. Measuring energy consumption is a crucial step towards obtaining energy efficiency. The instrumentation type and measurement technique vary according to the scope and type of equipment to be monitored.

Corporate-level tools commonly use a software-based instrumentation based on power models. They also group energy consumption information from several facilities to calculate corporate metrics, for example, Carbon Intensity. There are

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[4] http://trend.polito.it/

TABLE VIII
MEASURING AND MONITORING TOOLS SUMMARY

Scope	Monitoring Tool	Description	Instrumentation	Measurement Technique
Corporate	G.W.A.T.T. [96]	Simulator of networking technologies and architectures	Software-based	Model-based
	EARTH [134]	Framework to evaluate energy efficiency in a global scale	Software-based	Model-based
	Cloud Sustainability Dashboard [100]	Framework to quantify, assess and understand the overall impact of data center and clouds on sustainability	Software-based	Model-based
	Energy Tracking Tool [89]	Spreadsheet to assist small companies in tracking and monitoring energy levels, costs, and GHG emissions	Software-based	Model-based
	Cisco EnergyWise [101]	Framework to measure and control energy consumption and utilization of multiple data centers	Hardware-based and Software-based	Model-based and Direct
	DC Pro [103]	Spreadsheet to assist datacenter operators understanding and improving the energy efficiency	Software-based	Model-based
Facility	Energy Sensing [104]	Integrates energy data from several resources towards energy management. Also proposes a "smart box" to integrate and collect energy data from different resources.	Hardware-based and Software-based	Model-based and Direct
	ECO2Clouds Monitoring [105]	Distributed framework based on Zabbix to collect energy metrics in different granularity levels.	Hardware-based and Software-based	Model-based and Direct
	GreenHop [107]	Monitor climate changes in a server room	Hardware	Direct
	PowerAssure [110]	A solution relying on measurements tools such as Nagios, IBM Tivoli, to perform *e.g.*, real-time measurements, and reliability forecasts	Hardware-based and Software-based	Model-based and Direct
	Kwapi [111]	OpenStack-Ceilometer plugin to collect power information from various Wattmeters in the data center infrastructure	Hardware-based and Software-based	Model-based
Network	GreenSonar [52]	Tool to monitor energy efficiency based on power models and performance data acquired through perfSONAR.	Hardware-based and Software-based	Model-based
	EnergyAudit [115]	Provides a database of benchmark measurements, auditing tool querying data in the open database.	Hardware-based and Software-based	Model-based and Direct
	Trend [117]	Tool for monitoring power and utilization of network devices	Hardware-based	Direct
Equipment	Monitoring and Control MIB for Power and Energy RFC 7460 [118]	Defines a subset of the MIB for power and energy monitoring of devices	Non-invasive	Direct
	Energy Object Context MIB RFC 7461 [119]	Defines a module addressing device identification, context information, and the energy relationships between devices	Non-invasive	Direct
	Joulemeter [120]	Power metering at the virtual machine level. Based on existing instrumentation available on hypervisor	Software-based	Model-based
	RAPL (Running Average Power Limit) [123]	Intel power management interface for Linux servers	Software-based	Model-based
	Extended PAPI (Performance API) [129]	API to counters available on CPU and DRAM, to measure and report energy and power level	Software-based	Model-based

also approaches such as G.W.A.T.T. [96], which, although they do not collect energy information of facilities or simulated or emulated approaches, add great value by helping to estimate the effects of technologies such as SDN and NFV under known conditions of traffic and energy consumption. Tools/frameworks of this type can support business-level decisions, such as adopting a novel technology or architecture. It is also worth mentioning that the surveyed corporate-level tools combine different types of instrumentation and monitoring techniques, which may help in avoiding deploying many monitoring frameworks for the entire corporate infrastructure.

While network-level tools are restricted to network resources, facility monitoring tools extend this scope by addressing other resources available in a facility (*e.g.,* compute, storage, cooling) to calculate metrics such as PUE. Energy Sensing [104], for example, encompasses not only the modeling of consumption of network resources but also processing and storage in order to audit their efficiency. Another example that takes into account the trade-off between energy and reliability is the solution presented by PowerAssure [110]. Instead of using a software-based approach, the tool uses wattmeters and tools like Nagios and Zabbix to obtain power consumption information and then establish trade-offs considering power outages. These tools focus mainly on measuring the watts/bits ratio to calculate efficiency or reliability.

When it comes to the equipment, hardware-based and noninvasive instrumentation approaches are usually deployed because of their greater simplicity and accuracy, which might not be the case for sensor nodes. While the extra instrumentation is required for noninvasive (*e.g.,* SNMP/MIBs) and hardware-based approaches (*e.g.,* wattmeters), they do not require the implementation of a power model that is often not straightforward as a result of the number of components and capabilities that may impact equipment consumption.

The overhead in the communication channel is also a concern in this scope. In addition to potentially delaying delivery and calculating metrics, it can potentially lead to inaccuracy in the calculations if there is a loss of information on meter delivery. In this sense, approaches such as Hang *et al.* [135] that are based on machine learning techniques gain strength to avoid excessive communication and transmission delay. However, as a side effect, these techniques require the computational power of a sink or network-level node to run a machine learning algorithm, which implies an increase in overall energy consumption.

Another important aspect with the increasing demand from distributed clouds on optical infrastructures is to monitor energy efficiency and emissions of these devices. Typical optical monitoring includes the assessment of the amplifier control, channel, and signal quality in transmission and switching systems [136], [137], [138]. However, to the best of the authors' knowledge, there is a lack of tools to measure the consumption of such equipment. G.W.A.T.T allows some analysis, but it is not a network planning or dimensioning tool. Perhaps one reason for the lack of tools is the low applicability of rate-adaption or sleeping techniques in this environment. Such devices have a fixed consumption when active, which can be measured by devices such as wattmeters. Often, organizations use methods and manufacturers' data sheets or tools such as Energy Star's ETT to perform the necessary planning and operation calculations, including a safety margin. It might also be considered that facility tools, inside which the optical equipment coexists with the electronic equipment, are in some ways supporting the sustainable operation of these kinds of equipment. In any case, optical devices are by definition more energy efficient in comparison to electronic devices [90] and, at the same time, less (or not at all) flexible for sleeping/rating operations.

When it comes to components, for servers, the consumption of a number of components remains unaccounted by measurements reported through its interfaces, such as controller chip sets on the motherboard, network interface cards, etc. However, recent generation CPUs account for between 40 to 80% of the consumption of a server, depending on the actual configuration and load. Rack disaggregation, as exemplified by the Intel Rack Scale architecture, would help bring further simplification in this respect, isolating CPU trays from networking and storage trays and opening opportunities for more precise accounting of energy consumption for non-CPU trays.

To conclude, regarding the additional requirements listed on the beginning of this Section, we noticed that, among the available tools, almost all of them (when applicable, i.e., not an energy efficiency simulator or spreadsheet), support real-time energy measurements, according to traffic load, in different time granularities and aggregation levels, with some sort of historical data storage. However, rare are the mentions to support for custom metrics as suggested by [94], and the report (quant- or qualitatively) of confidence levels of the measurements as suggested by [69].

V. CONCLUSION AND FUTURE WORK DIRECTIONS

In this work, we surveyed prior work related to green metrics, measurement methods, and measurement tools. Regarding the metrics, we situated the similar ones, and it was possible to see that the PUE, ECR, and TEER groups are the most popular ones. Moreover, we noticed that fewer metrics related to GHG emissions exist. One interesting matter to observe is that, despite the lack of consensus on which metrics to use, the majority of these metrics addresses the following aspects: performance, power/energy, emissions information. However, in many cases, the time component of the performance (good for, e.g., evaluate delay) is not present. Future work on metrics has to address that, mainly considering the stringent latency requirements of the next generation of mobile networks. To conclude in that respect, selected new ICT developments, such as ICN and CORD, but not all developments can be supported by existing metrics. IoT supporting infrastructure requires the definition of a holistic set of metrics from an end-to-end perspective as soon as possible.

The evaluation of how to measure energy and which emissions occur in the current and upcoming technologies is essential, ensuring that not only specific solutions for selected technologies or use cases are developed, but a general approach is needed to enable constant metrics adjustments with every new solution appearing. Also following existing alignment efforts between different groups and institutions, collaborative efforts are crucial for building a consensus not only for distributed clouds, but also for other infrastructures.

With respect to those methods evaluated within this survey, prior work shows a range of non-invasive and model-based solutions that, regardless of not being readily available or implemented, can provide a good basis for tools, either to implement or to improve them. The GHG accounting methods are gaining momentum, and taking a temporally differentiated approach is promising, as indicated in the ongoing standardization effort by IEEE [139].

As for the tools, we noticed that each scope has a tendency for one specific instrumentation and measurement technique. Besides, there is a lack of tools targeting optical infrastructures, which are increasingly demanded in distributed cloud scenarios. It is important to evaluate in the future if the existing methods or facility tools are fully in support of the planning and operation of such networks; since optical devices are known to be more energy efficient than electronic ones. Prior work with sensors can be implemented to supply the end-to-end view that IoT infrastructures demand.

Additionally, future work on tools has to address the lack of confidence level analysis and customizable metrics, which holds true, too, for an easy integration of tools as well. Despite of those efforts as pointed out by [104], a lack of standardized interfaces between the different types of equipment is

TABLE IX
SUMMARY OF THE FINDINGS AND FUTURE WORK DIRECTIONS

	Findings	**Future work**
Metrics	• PUE, ECR, and TEER groups are the most popular. • GHG-related metrics are fewer, but gaining momentum. • Many metrics have a lot of similarities. • There is no consensus on the best composite metrics to use for distributed cloud networks, despite some collaborative works among groups and institutes. • Even without the consensus, metrics are in general composed by a performance part, power/energy, and emissions information.	• Evaluate the delay representation in the performance part of metrics in order to support distributed cloud operations and forthcoming mobile infrastructures. • Discuss and develop metrics to support an end-to-end view of IoT infrastructures. • Strengthen collaborative efforts to reach consensus on composite metrics necessary for distributed cloud infrastructures support.
Methods	• Interesting set of noninvasive and model-based solutions that might be a good base for implementing tools. • GHG accounting methods gaining momentum to support distributed cloud infrastructures.	• Ongoing efforts on standardizing GHG accounting for improved accuracy.
Tools	• Each scope has a tendency for one instrumentation and one measurement technique • Some tools are not available in source codes or for download, but many of them are (e.g., at GitHub).	• Address evaluation of optical infrastructures. • Addressing the IoT infrastructure end-to-end view. • Tools need to support evaluation of confidence levels and customizable metrics. • Evaluation and proposal of standardized interfaces for integration.

observed. This leads in case of more complex scenarios to increasing volumes of data and in case of IoT devices to inherently heterogeneity to be handled. Therefore, Table IX summarizes the key findings and future work for each major aspect identified.

While conducting the literature study for this survey, we observed a number of apparent disconnects between hierarchical levels included in Figure 2. For example, even though operators such as Verizon and Deutsche Telekom brought novel definitions of energy efficiency metrics and routinely gather and publish such data on their own infrastructure, SLAs associated to services provided by them contain no sustainability-related parameters [18], [140]. The CORD initiative has yet to specify which green energy metrics and tools they recommend to be part of their framework. Public cloud providers also, to date, have no public SLA template in which energy sources and energy consumption would feature highly. This is despite such providers being very vocal and open with respect to the mix of energy sources they utilize and setting increasing goals for the use of renewable energy. The industry and academia could take further steps towards developing viable GreenSLAs that could be offered to customers by furthering agreements on metrics and addressing scalability and timeliness challenges related to interconnecting data and control infrastructures of distributed clouds and smart grids.

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REFERENCES

[1] AB Ericsson, "Ericsson Mobility Report," *Ericsson, Sweden, Tech. Rep. EAB-17*, vol. 005964 Uen, Revision B, June 2017. [Online]. Available: https://www.ericsson.com/assets/local/mobility-report/documents/2017/ericsson-mobility-report-june-2017.pdf

[2] L. Peterson, A. Al-Shabibi, T. Anshutz, S. Baker, A. Bavier, S. Das, J. Hart, G. Palukar, and W. Snow, "Central office re-architected as a data center," *IEEE Communications Magazine*, vol. 54, no. 10, pp. 96–101, 2016.

[3] B. Camus, F. Dufossé, and A.-C. Orgerie, "A stochastic approach for optimizing green energy consumption in distributed clouds," in *SMARTGREENS: International Conference on Smart Cities and Green ICT Systems*, 2017.

[4] A. Khosravi and R. Buyya, "Energy and carbon footprint-aware management of geo-distributed cloud data centers: A taxonomy, state of the art," *Advancing Cloud Database Systems and Capacity Planning With Dynamic Applications*, p. 27, 2017.

[5] J. Whitney and P. Delforge, "Data center efficiency assessment," *Issue paper on NRDC (The Natural Resource Defense Council)*, 2014.

[6] T. Wei, M. A. Islam, S. Ren, and Q. Zhu, "Co-scheduling of datacenter and hvac loads in mixed-use buildings," in *2016 Seventh International Green and Sustainable Computing Conference (IGSC)*, Nov 2016, pp. 1–8.

[7] C. H. Chou, L. N. Bhuyan, and S. Ren, "Tailcut: Power reduction under quality and latency constraints in distributed search systems," in *2017 IEEE 37th International Conference on Distributed Computing Systems (ICDCS)*, June 2017, pp. 1465–1475.

[8] A. P. Bianzino, A. K. Raju, and D. Rossi, "Apples-to-apples: a framework analysis for energy-efficiency in networks," *ACM SIGMETRICS Performance Evaluation Review*, vol. 38, no. 3, pp. 81–85, 2011.

[9] X. Wang, A. V. Vasilakos, M. Chen, Y. Liu, and T. T. Kwon, "A survey of green mobile networks: Opportunities and challenges," *Mobile Networks and Applications*, vol. 17, no. 1, pp. 4–20, 2012.

[10] Facebook, "Prineville Data Center," Facebook, Tech. Rep., 2016. [Online]. Available: https://www.facebook.com/PrinevilleDataCenter/app/399244020173259

[11] ETSI, "ES 103 117 v1.1.1," *Environmental Engineering (EE); Principles for Mobile Network level energy efficiency*, 2012.

[12] Ericsson, "The Greening of Telecom at the Edge and Metro - Redefining the edge and metro to reduce environmental impact and OpEx," 2010.

[13] M. E. Haque, K. Le, Í. Goiri, R. Bianchini, and T. D. Nguyen, "Providing green SLAs in high performance computing clouds," in *Green Computing Conference (IGCC), 2013 International*. IEEE, 2013, pp. 1–11.

[14] R. Zhou, Y. Shi, and C. Zhu, "Axpue: Application level metrics for

power usage effectiveness in data centers," in *Big Data, 2013 IEEE International Conference on*. IEEE, 2013, pp. 110–117.

[15] ITU-T, "L.1320: Energy efficiency metrics and measurement for power and cooling equipment for telecommunications and data centres," *Series L: Construction, Installation and Protection of Cables and Other Elements of Outside Plant*, 2014.

[16] T. Chen, H. Kim, and Y. Yang, "Energy efficiency metrics for green wireless communications," in *2010 International Conference on Wireless Communications Signal Processing (WCSP)*, Oct 2010, pp. 1–6.

[17] W. B. C. for Sustainable Development and W. R. Institute, *The greenhouse gas protocol: a corporate accounting and reporting standard*. World Resources Inst, 2001.

[18] Verizon, "2015 Corporate Responsibility Supplement," Verizon, New York, NY, USA, Tech. Rep., 2015. [Online]. Available: http://www.verizon.com/about/sites/default/files/annual/verizon-annual-2015/downloads/2015_Verizon_Corporate_Responsibility_Supplement.pdf

[19] A. Amokrane, M. F. Zhani, Q. Zhang, R. Langar, R. Boutaba, and G. Pujolle, "On satisfying green SLAs in distributed clouds," in *Network and Service Management (CNSM), 2014 10th International Conference on*. IEEE, 2014, pp. 64–72.

[20] eBay, "Digital Service Efficiency," 2013, accessed: 21 Dec. 2016. [Online]. Available: http://www.ebaytechblog.com/wp-content/uploads/2013/03/FINAL_DSE-Solution-Paper.pdf

[21] M. Erol-Kantarci and H. T. Mouftah, "Energy-Efficient Information and Communication Infrastructures in the Smart Grid: A Survey on Interactions and Open Issues," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 1, pp. 179–197, Firstquarter 2015.

[22] The Green Grid, "Harmonizing Global Metrics for Data Center Energy Efficiency," Technical report, Global Taskforce Reaches Agreement on Measurement Protocols for Datacenter Productivity, Tech. Rep., Mar. 2014.

[23] C. Fiandrino, D. Kliazovich, P. Bouvry, and A. Zomaya, "Performance and Energy Efficiency Metrics for Communication Systems of Cloud Computing Data Centers," *IEEE Transactions on Cloud Computing*, Apr. 2015.

[24] ISO, "Webpage of the Technical Committee ISO/IEC JTC 1/SC 39 Sustainability for and by Information Technology," accessed: 13 Jan. 2016. [Online]. Available: https://www.iso.org/committee/654019.html

[25] J. Mitchell-Jackson, J. G. Koomey, B. Nordman, and M. Blazek, "Data center power requirements: measurements from Silicon Valley," *Energy*, vol. 28, no. 8, pp. 837–850, 2003.

[26] L. Wang and S. U. Khan, "Review of performance metrics for green data centers: a taxonomy study," *The Journal of Supercomputing*, vol. 63, no. 3, pp. 639–656, 2013. [Online]. Available: http://dx.doi.org/10.1007/s11227-011-0704-3

[27] R. Sharma, A. Shah, C. Bash, T. Christian, and C. Patel, "Water Efficiency Management in Datacenters (Part I): Introducing a water usage metric based on available energy consumption," *Hewlett-Packard Laboratories Technical Report, HPL-2008-206*, 2008.

[28] M. Imran, J. Alonso-Rubio, G. Auer, M. Boldi, M. Braglia, P. Fazekas, D. Ferling, A. Fehske, P. Frenger, R. Gupta *et al.*, "Most suitable efficiency metrics and utility functions," *EARTH Project Report*, pp. 1–55, January 2012.

[29] ETSI, "Final draft ETSI ES 205 200-3 V1.0.0," *Access, Terminals, Transmission and Multiplexing (ATTM); Energy management; Global KPIs; Operational infrastructures; Part 3: Global KPIs for ICT sites*, 2017.

[30] ETSI, "ETSI TS 102 533 V1.1.1," *Environmental Engineering (EE) Measurement Methods and limits for Energy Consumption in Broadband Telecommunication Networks Equipment*, 2008.

[31] C. Han, T. Harrold, S. Armour, I. Krikidis, S. Videv, P. M. Grant, H. Haas, J. S. Thompson, I. Ku, C. X. Wang, T. A. Le, M. R. Nakhai, J. Zhang, and L. Hanzo, "Green radio: radio techniques to enable energy-efficient wireless networks," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 46–54, June 2011.

[32] ETSI, "TS 102 706 v1.2.1," *Environmental Engineering (EE) Measurement Method for Energy Efficiency of Wireless Access Network Equipment*, 2011.

[33] ETSI, "ES 201 554 v1.2.0," *Environmental Engineering (EE); Measurement method for Energy efficiency of Mobile Core network and Radio Access Control equipment*, 2014.

[34] ETSI, "ES 203 228-1 v1.1.1," *Environmental Engineering (EE); Assessment of mobile network energy efficiency*, 2015.

[35] ITU-T, "L.1330: Energy efficiency measurement and metrics for telecommunication networks," *Series L: Construction, Installation and Protection of Cables and Other Elements of Outside Plant*, 2015.

[36] ITU-T, "L.1310: Energy efficiency metrics and measurement for telecommunication equipment," *Series L: Construction, Installation and Protection of Cables and Other Elements of Outside Plant*, 2014.

[37] F. Richter, A. J. Fehske, and G. P. Fettweis, "Energy Efficiency Aspects of Base Station Deployment Strategies for Cellular Networks," in *2009 IEEE 70th Vehicular Technology Conference Fall*, Sept 2009, pp. 1–5.

[38] C. Fang, F. R. Yu, T. Huang, J. Liu, and Y. Liu, "A Survey of Green Information-Centric Networking: Research Issues and Challenges," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 3, pp. 1455–1472, thirdquarter 2015.

[39] S. Lafond and T. A. Trinh, "Energy efficient thresholds for cached content in content centric networking," in *2013 24th Tyrrhenian International Workshop on Digital Communications - Green ICT (TIWDC)*, Sept 2013, pp. 1–6.

[40] ECR Initiative and others, "Network and Telecom Equipment-Energy and Performance (Assessment Metrics, Test Procedure and Measurement Methodology)," 2010.

[41] S. H. Jeon, H. Oh, H. Lee, and J. Choi, "Issues and prospects for energy saving networks," in *2012 International Conference on ICT Convergence (ICTC)*. IEEE, 2012, pp. 201–204.

[42] D. Minoli, *Designing Green Networks and Network Operations: Saving Run-the-Engine Costs*. CRC Press, 2011. [Online]. Available: https://books.google.ca/books?id=50_RBQAAQBAJ

[43] P. Mahadevan, P. Sharma, S. Banerjee, and P. Ranganathan, "A power benchmarking framework for network devices," in *International Conference on Research in Networking*. Springer, 2009, pp. 795–808.

[44] V. Manral, P. Sharma, S. Banerjee, and Y. Ping, "Benchmarking Power usage of networking devices," Working Draft, IETF Secretariat, Internet-Draft draft-manral-bmwg-power-usage-04, March 2013. [Online]. Available: https://tools.ietf.org/html/draft-manral-bmwg-power-usage-04

[45] H. Hamdoun, P. Loskot, T. O'Farrell, and J. He, "Survey and applications of standardized energy metrics to mobile networks," *annals of telecommunications - annales des télécommunications*, vol. 67, no. 3, pp. 113–123, 2012. [Online]. Available: http://dx.doi.org/10.1007/s12243-012-0285-z

[46] ETSI, "ETSI ES 203 184 V1.1.1," *Environmental Engineering (EE); Measurement Methods for Power Consumption in Transport Telecommunication Networks Equipment*, 2013.

[47] T. Talbot and H. Davis, "Verizon NEBS TM Compliance: Energy Efficiency Requirements for Telecommunications Equipment - Issue 6," Verizon, Tech. Rep. VZ. TPR. 9205, Tech. Rep., 2016.

[48] Y. Zhang, P. Chowdhury, M. Tornatore, and B. Mukherjee, "Energy efficiency in telecom optical networks," *IEEE Communications Surveys & Tutorials*, vol. 12, no. 4, pp. 441–458, 2010.

[49] D. Kharitonov, "Energy Efficiency for ICT (Network/Telecom Group) Problem Space, Metrics, Gaps," Juniper, Tech. Rep., Tech. Rep., 2008.

[50] M. Parker and S. Walker, "Roadmapping ICT: An Absolute Energy Efficiency Metric," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 3, no. 8, pp. A49–A58, August 2011.

[51] Z. Hasan, H. Boostanimehr, and V. K. Bhargava, "Green Cellular Networks: A Survey, Some Research Issues and Challenges," *IEEE Communications Surveys & Tutorials*, vol. 13, no. 4, pp. 524–540, Fourth 2011.

[52] L. Engels and T. Yakimov, "GreenSONAR: A multi-domain energy profiling system based on perfSONAR," University of Amsterdam, Tech. Rep., 2013.

[53] L. Zhao, J. Cai, and H. Zhang, "Radio-Efficient Adaptive Modulation and Coding: Green Communication Perspective," in *2011 IEEE 73rd Vehicular Technology Conference (VTC Spring)*, May 2011, pp. 1–5.

[54] W. Wang, Z. Zhang, and A. Huang, *Towards Green Wireless Communications: Metrics, Optimization and Tradeoff*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 23–36. [Online]. Available: http://dx.doi.org/10.1007/978-3-642-22179-8_2

[55] L. Suarez, L. Nuaymi, and J.-M. Bonnin, "An overview and classification of research approaches in green wireless networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 2012, no. 1, p. 142, 2012. [Online]. Available: http://dx.doi.org/10.1186/1687-1499-2012-142

[56] M. Nasimi, F. Hashim, and C. K. Ng, "Characterizing energy efficiency for heterogeneous cellular networks," in *2012 IEEE Student Conference on Research and Development (SCOReD)*, Dec 2012, pp. 198–202.

[57] Smart City Cluster Collaboration, "Existing Data Centres energy metrics – Task 1," Smart City Cluster Collaboration, Tech. Rep., Feb 2014. [Online]. Available: http://www.dolfin-fp7.eu/wp-content/uploads/2014/01/Task-1-List-of-DC-Energy-Related-Metrics-Final.pdf

[58] "Global Leaders from Industry and Government Reach Agreement for Measuring Data Center Energy Productivity," accessed: 17 Sep. 2017. [Online]. Available: https://www.thegreengrid.org/en/newsroom/news-releases/global-leaders-industry-and-government-reach-agreement-measuring-data-center

[59] C. Ge, Z. Sun, N. Wang, K. Xu, and J. Wu, "Energy Management in Cross-Domain Content Delivery Networks: A Theoretical Perspective," *IEEE Transactions on Network and Service Management*, vol. 11, no. 3, pp. 264–277, Sept 2014.

[60] A. C. Riekstin, T. Dandres, K. K. Nguyen, R. Samson, and M. Cheriet, "Monitoring and Measurement System for Green Operation of Geographically Distributed ICT Services," in *International Workshop on Green ICT and Smart Networking (GISN 2016)*. IEEE, 2016, p. to appear.

[61] K. K. Nguyen, M. Cheriet, M. Lemay, V. Reijs, A. Mackarel, and A. Pastrama, "Environmental-aware virtual data center network," *Computer Networks*, vol. 56, no. 10, pp. 2538–2550, 2012.

[62] R. Bolla, R. Bruschi, and C. Lombardo, "Standard Methodologies for Energy Efficiency Assessment," in *Green Communications: Theoretical Fundamentals, Algorithms and Applications. Auerbach Publications*, J. Wu, S. Rangan, and H. Zhang, Eds. United States: CRC Press, 2012, ch. 4.

[63] Z. Abbas and W. Yoon, "A survey on energy conserving mechanisms for the internet of things: Wireless networking aspects," *Sensors*, vol. 15, no. 10, pp. 24 818–24 847, 2015.

[64] M. I. Robles and P. Jokela, "Design of a Performance Measurements Platform in Lightweight M2M for Internet of Things," in *IRTF & ISOC Workshop on Research and Applications of Internet Measurements (RAIM)*, 2015.

[65] LoRa Alliance, "LoRaWAN Specification," *LoRa Alliance*, 2015.

[66] T. O'Farrell and S. Fletcher, *Green Communication Concepts, Energy Metrics and Throughput Efficiency for Wireless Systems*. John Wiley & Sons, Ltd, 2015, pp. 19–42. [Online]. Available: http://dx.doi.org/10.1002/9781118759257.ch2

[67] J. Alshudukhi, S. Ou, P. Ball, L. Zhao, and G. Zhao, "Energy efficiency metrics for low-power near ground level wireless sensors," in *2015 IEEE 11th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, Oct 2015, pp. 329–335.

[68] J. Baliga, R. Ayre, K. Hinton, W. V. Sorin, and R. S. Tucker, "Energy Consumption in Optical IP Networks," *J. Lightwave Technol.*, vol. 27, no. 13, pp. 2391–2403, Jul 2009. [Online]. Available: http://jlt.osa.org/abstract.cfm?URI=jlt-27-13-2391

[69] J. Quittek, R. Winter, T. Dietz, B. Claise, and M. Chandramouli, "Requirements for Energy Management," RFC 6988, DOI 10.17487/rfc6988, Sep. 2013. [Online]. Available: https://rfc-editor.org/rfc/rfc6988.txt

[70] H. Pirzadeh and A. Hamou-Lhadj, "A View of Monitoring and Tracing Techniques and Their Application to Service-Based Environments," in *Multimedia Services in Intelligent Environments*. Springer, 2010, pp. 49–62.

[71] D. Dudkowski and K. Samdanis, "Energy consumption monitoring techniques in communication networks," in *2012 IEEE Consumer Communications and Networking Conference (CCNC)*, 2012.

[72] K.-K. Nguyen, M. Cheriet, M. Lemay, M. Savoie, and B. Ho, "Powering a data center network via renewable energy: A green testbed," *Internet Computing, IEEE*, vol. 17, no. 1, pp. 40–49, 2013.

[73] CSA Group, "ICT Protocol - Version 1: ICT Greenhouse Gas Reduction Project Protocol: Quantification and Reporting," CSA Group, Tech. Rep., 2012. [Online]. Available: http://csa.ca

[74] ITU-T, "L.1420: Methodology for energy consumption and greenhouse gas emissions impact assessment of information and communication technologies in organizations," *Series L: Construction, Installation and Protection of Cables and Other Elements of Outside Plant*, feb 2012.

[75] ITU-T, "L.1400: Overview and general principles of methodologies for assessing the environmental impact of information and communication technologies," *Series L: Construction, Installation and Protection of Cables and Other Elements of Outside Plant*, feb 2011.

[76] ITU-T, "L.1430: Methodology for assessment of the environmental impact of information and communication technology greenhouse gas and energy projects," *Series L: Construction, Installation and Protection of Cables and Other Elements of Outside Plant*, dec 2013.

[77] ITU-T, "L.1440: Methodology for environmental impact assessment of information and communication technologies at city level," *Series L: Construction, Installation and Protection of Cables and Other Elements of Outside Plant*, oct 2015.

[78] N. A. Ryan, J. X. Johnson, and G. A. Keoleian, "Comparative assessment of models and methods to calculate grid electricity emissions," *Environmental Science & Technology*, vol. 50, no. 17, pp. 8937–8953, 2016, pMID: 27499211. [Online]. Available: http://dx.doi.org/10.1021/acs.est.5b05216

[79] E. Maurice, T. Dandres, R. Farrahi Moghaddam, K. Nguyen, Y. Lemieux, M. Cherriet, and R. Samson, "Modelling of Electricity Mix in Temporal Differentiated Life-Cycle-Assessment to Minimize Carbon Footprint of a Cloud Computing Service," in *ICT for Sustainability 2014 (ICT4S-14)*. Atlantis Press, 2014.

[80] J. Wu, S. Guo, J. Li, and D. Zeng, "Big Data Meet Green Challenges: Big Data Toward Green Applications," *IEEE Systems Journal*, vol. 10, no. 3, pp. 888–900, Sept 2016.

[81] ITU-T, "L.1410: Methodology for environmental life cycle assessments of information and communication technology goods, networks and services," *Series L: Construction, Installation and Protection of Cables and Other Elements of Outside Plant*, dec 2014.

[82] ETSI, "TS 203 199 v1.1.1," *Environmental Engineering (EE); Methodology for environmental Life Cycle Assessment (LCA) of Information and Communication Technology (ICT) goods, networks and services*, feb 2015.

[83] J. Baliga, R. Ayre, K. Hinton, and R. S. Tucker, "Energy consumption in wired and wireless access networks," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 70–77, June 2011.

[84] K. Hinton, F. Jalali, and A. Matin, "Energy consumption modelling of optical networks," *Photonic Network Communications*, vol. 30, no. 1, pp. 4–16, 2015. [Online]. Available: http://dx.doi.org/10.1007/s11107-015-0491-5

[85] ETSI, "Environmental Engineering (EE): Green Abstraction Layer (GAL); Power management capabilities of the future energy telecommunication fixed network nodes," European Telecommunications Standards Institute, Sophia Antipolis Cedex, France, Tech. Rep., Mar. 2014.

[86] B. Krishnan, H. Amur, A. Gavrilovska, and K. Schwan, "VM power metering: feasibility and challenges," *ACM SIGMETRICS Performance Evaluation Review*, vol. 38, no. 3, pp. 56–60, 2011.

[87] K. Samdanis, M. Paul, T. Kessler, and R. Winter, "Energy Efficiency Standards for Wireline Communications," in *Green Communications: Principles, Concepts and Practice*, K. Samdanis, P. Rost, A. Maeder, M. Meo, and C. Verikoukis, Eds. United Kingdom: John Wiley & Sons, 2015, ch. 20, pp. 377–394.

[88] F. F. Moghaddam, R. F. Moghaddam, and M. Cheriet, "Carbon metering and effective tax cost modeling for virtual machines," in *Cloud Computing (CLOUD), 2012 IEEE 5th International Conference on*. IEEE, 2012, pp. 758–763.

[89] Energy Star, "Energy Tracking Tool - Quick Start Guide," 2015, accessed: 01 May. 2017. [Online]. Available: https://www.energystar.gov/sites/default/files/tools/Energy%20Tracking%20Tool%20Quick%20Start%20Guide_04052015%20Accessible%281%29.pdf

[90] C. Despins, F. Labeau, R. Labelle, M. Cheriet, A. Leon-Garcia, and O. Cherkaoui, "Green Communications for Carbon Emission Reductions: Architectures and Standards," in *Green Communications: Theoretical Fundamentals, Algorithms and Applications. Auerbach Publications*, J. Wu, S. Rangan, and H. Zhang, Eds. United States: CRC Press, 2012, ch. 6.

[91] B. Martinez, M. Montón, I. Vilajosana, and J. D. Prades, "The power of models: Modeling power consumption for IoT devices," *IEEE Sensors Journal*, vol. 15, no. 10, pp. 5777–5789, 2015.

[92] C. Jacquenet, Y. Lair, F. L. Faucheur, K. J. Ma, A. J. Mahoney, B. Rosen, T. B. Terriberry, M. Zanaty, R. Even, B. Gondwana, B. Leiba, S. Mansfield, B. Gracie, J. Elmirghanni, G. Camarillo, R. Sparks, and R. Housley, "Standards News," *IEEE Communications Standards Magazine*, vol. 1, no. 2, pp. 13–19, 2017.

[93] ITU-T, "Rec. Y.3022," *Measuring energy in networks*, 2014.

[94] J. Lin, R. Ravichandiran, H. Bannazadeh, and A. Leon-Garcia, "Monitoring and measurement in software-defined infrastructure," in *Integrated Network Management (IM), 2015 IFIP/IEEE International Symposium on*. IEEE, 2015, pp. 742–745.

[95] P. Racz, D. Dönni, and B. Stiller, "An architecture and implementation for IP Network and Service Quality Measurements," in *2010 IEEE Network Operations and Management Symposium - NOMS 2010*, April 2010, pp. 24–31.

[96] Nokia Bell Labs, "G.W.A.T.T. (Global What If Analyzer of NeTwork Energy ConsumpTion," Nokia Bell Labs, Tech. Rep., June 2015. [Online]. Available: https://media-bell-labs-com.s3.amazonaws.com/pages/20150114_1907/GWATT_WhitePaper.pdf

[97] J. Elmirghani, T. Klein, K. Hinton, T. eh El-Gorashi, A. Lawey, and X. Dong, "GreenTouch GreenMeter core network power consumption

models and results," in *Green Communications (OnlineGreencomm), 2014 IEEE Online Conference on*. IEEE, 2014, pp. 1–8.

[98] GeSI, "SMARTer 2030: ICT Solutions for 21st Century Challenges," The Climate Group on behalf of the Global eSustainability Initiative (GeSI), Brussels, Belgium, Tech. Rep., 2015. [Online]. Available: http://smarter2030.gesi.org/

[99] "G.W.A.T.T website," accessed: 12 Dec. 2016. [Online]. Available: http://gwatt.net/network

[100] M. Arlitt, S. Banerjee, C. Bash, Y. Chen, D. Gmach, C. Hoover, P. Mahadevan, D. Milojicic, E. Pelletier, R. Vishwanath *et al.*, "Cloud sustainability dashboard," in *Sustainable Systems and Technology (ISSST), 2010 IEEE International Symposium on*. IEEE, 2010, pp. 1–1.

[101] "Cisco EnergyWise Suite," accessed: 15 Sep. 2017. [Online]. Available: https://www.cisco.com/c/en/us/products/switches/energy-management-technology/at-a-glance-listing.html

[102] "Energy Tracking Tool - Download," accessed: 15 Sep. 2017. [Online]. Available: https://www.energystar.gov/buildings/tools-and-resources/energy-tracking-tool

[103] "Data Center Profiler (DC Pro)," accessed: 21 Sep. 2017. [Online]. Available: https://datacenters.lbl.gov/tools/1-dc-pro-tools

[104] J. L. Pan, S. Z. Chen, R. Jain, and S. Paul, "Energy Sensing and Monitoring Framework with an Integrated Communication Backbone in the Energy Efficient Intelligent Buildings," in *Applied Mechanics and Materials*, vol. 303. Trans Tech Publ, 2013, pp. 1460–1464.

[105] A. Tenschert, P. Skvortsov, and M. Gienger, "Eco-Efficient Cloud Resource Monitoring and Analysis." in *ICT4S (Workshops)*, 2014, pp. 14–17.

[106] "ECO2Clouds source code repository," accessed: 15 Sep. 2017. [Online]. Available: https://github.com/ECO2Clouds/r2

[107] D. S. Camargo, C. C. Miers, G. P. Koslovski, and M. A. Pillon, "GreenHop: Open source environmental monitoring for small and medium data centers," in *2016 35th International Conference of the Chilean Computer Science Society (SCCC)*, Oct 2016, pp. 1–12.

[108] G. Dini and M. Tiloca, "Considerations on security in zigbee networks," in *Sensor Networks, Ubiquitous, and Trustworthy Computing (SUTC), 2010 IEEE International Conference on*. IEEE, 2010, pp. 58–65.

[109] "GreenHop source code repository," accessed: 15 Sep. 2017. [Online]. Available: https://github.com/DanielFloripa/GreenHop

[110] PowerAssure, "Isolating Applications from Power Problems to Maximize Availability," PowerAssure Inc, Tech. Rep., June 2014.

[111] OpenStack, "Kwapi," OpenStack, Tech. Rep., Jun 2016. [Online]. Available: http://kwapi.readthedocs.io/en/latest/

[112] "Kwapi source code repository," accessed: 15 Sep. 2017. [Online]. Available: https://github.com/openstack/kwapi

[113] V. Cima, B. Grazioli, S. Murphy, and T. M. Bohnert, "Adding energy efficiency to Openstack," in *Sustainable Internet and ICT for Sustainability (SustainIT), 2015*. IEEE, 2015, pp. 1–8.

[114] B. Tierney, J. Metzger, J. Boote, E. Boyd, A. Brown, R. Carlson, M. Zekauskas, J. Zurawski, M. Swany, and M. Grigoriev, "perfsonar: Instantiating a global network measurement framework," *SOSP Wksp. Real Overlays and Distrib. Sys*, 2009.

[115] J. Chabarek and P. Barford, "Energy Audit: Monitoring power consumption in diverse network environments," in *Green Computing Conference (IGCC), 2013 International*. IEEE, 2013, pp. 1–10.

[116] "EnergyAudit source code repository," accessed: 15 Sep. 2017. [Online]. Available: https://github.com/jc-wail/WAIL/tree/master/EnergyAudit

[117] L. Chiaraviglio, R. Bruschi, A. Cianfrani, O. M. J. Ortiz, and G. Koutitas, "The trend meter: Monitoring the energy consumption of networked devices," *International Journal of Business Data Communications and Networking (IJBDCN)*, vol. 9, no. 2, pp. 27–44, 2013.

[118] M. Chandramouli, B. Claise, B. Schoening, J. Quittek, and T. Dietz, "Monitoring and Control MIB for Power and Energy," Internet Requests for Comments, RFC Editor, RFC 7460, March 2015.

[119] J. Parello, B. Claise, and M. Chandramouli, "Energy Object Context MIB," RFC 7461, DOI 10.17487/RFC7461, Mar. 2015. [Online]. Available: https://www.rfc-editor.org/info/rfc7461

[120] A. Kansal, F. Zhao, J. Liu, N. Kothari, and A. A. Bhattacharya, "Virtual machine power metering and provisioning," in *Proceedings of the 1st ACM symposium on Cloud computing*. ACM, 2010, pp. 39–50.

[121] Cisco, "Cisco Energy Management," Cisco, Tech. Rep., March 2017. [Online]. Available: https://cem-update.cisco.com/download/files/5.2.0/docs/CEM_Online_Help/content/guide/general-concepts/IPMI.htm

[122] W. Fischer, "IPMI Basics," Thomas Krenn AG, Tech. Rep., Mar. 2017. [Online]. Available: https://www.thomas-krenn.com/en/wiki/IPMI_Basics

[123] 01.org, Intel Open Source Community, "RAPL Power Meter," accessed: 26 Sep. 2017. [Online]. Available: https://01.org/rapl-power-meter

[124] "Intel 64 and IA-32 Architectures Software Developer's Manual," accessed: 25 Sep. 2017. [Online]. Available: https://software.intel.com/sites/default/files/managed/7c/f1/253669-sdm-vol-3b.pdf

[125] , ","accessed: 26 Sep. 2017. [Online]. Available: http://web.eece.maine.edu/~vweaver/projects/rapl/rapl_validation.html

[126] H. Zhang and H. Hoffman, "A quantitative evaluation of the rapl power control system," *Feedback Computing*, 2015.

[127] S. Desrochers, C. Paradis, and V. M. Weaver, "A validation of dram rapl power measurements," in *Proceedings of the Second International Symposium on Memory Systems*. ACM, 2016, pp. 455–470.

[128] Innovative Computing Laboratory, "PAPI Overview," accessed: 26 Sep. 2017. [Online]. Available: http://icl.cs.utk.edu/papi/overview/index.html

[129] V. M. Weaver, M. Johnson, K. Kasichayanula, J. Ralph, P. Luszczek, D. Terpstra, and S. Moore, "Measuring energy and power with papi," in *2012 41st International Conference on Parallel Processing Workshops*, Sept 2012, pp. 262–268.

[130] H. Jagode, A. YarKhan, A. Danalis, and J. Dongarra, *Power Management and Event Verification in PAPI*. Cham: Springer International Publishing, 2016, pp. 41–51. [Online]. Available: https://doi.org/10.1007/978-3-319-39589-0_4

[131] Q. Liu, V. Jimenez, M. Moreto, J. Abella, F. J. Cazorla, and M. Valero, "Per-task energy accounting in computing systems," *IEEE Computer Architecture Letters*, vol. 13, no. 2, pp. 85–88, July 2014.

[132] Siemens, "Efficiency Monitoring," accessed: 30 Mar. 2017. [Online]. Available: http://www.buildingtechnologies.siemens.com/bt/global/en/building-solutions/bps/strategy-planning/efficiency-monitoring/pages/efficiency-monitoring.aspx

[133] ABB, "Industrial energy monitoring and reporting software," accessed: 30 Mar. 2017. [Online]. Available: http://new.abb.com/cpm/energy-manager/energy-monitoring-and-reporting

[134] M. Imran and E. Katranaras, "Energy efficiency analysis of the reference systems, areas of improvements and target breakdown. ICT-EARTH Project, Deliverable D2.3, Updated, EC-IST Office, Brussels, Belgium (January 2012)."

[135] R. Huang, X. Chu, J. Zhang, and Y. H. Hu, "Energy-Efficient Monitoring in Software Defined Wireless Sensor Networks Using Reinforcement Learning: A Prototype," *International Journal of Distributed Sensor Networks*, vol. 11, no. 10, p. 360428, 2015. [Online]. Available: http://dx.doi.org/10.1155/2015/360428

[136] D. Kilper, R. Bach, D. Blumenthal, D. Einstein, T. Landolsi, L. Ostar, M. Preiss, and A. Willner, "Optical performance monitoring," *Journal of Lightwave Technology*, vol. 22, no. 1, pp. 294–304, 2004.

[137] M. Coates, Y. Pointurier, and M. Rabbat, "Compressed network monitoring for IP and all-optical networks," in *Proceedings of the 7th ACM SIGCOMM conference on Internet measurement*. ACM, 2007, pp. 241–252.

[138] A. Chaudhary, "Analysis of Q-Factor Monitoring in Optical Network," *Transaction on Electron Optics*, vol. 1, no. 2, 2015.

[139] GreenICT, "IEEE GreenICT," IEEE, Tech. Rep., 2016. [Online]. Available: http://greenict.ieee.org/

[140] Deutsche, "IP Transit. Technical product sheet," Deutsche Telekom, Tech. Rep., 2015. [Online]. Available: http://www.telekom-icss.com/iptransit

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