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RESEARCH ARTICLE

Analysis of Energy Intensity and Generic Energy Efficiency Metrics in Communication Networks: Limits, Practical Applications, and Case Studies

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ABSTRACT Energy intensity is the ratio between energy consumed and data volume over a certain time frame. It is frequently used as a metric to indicate the energy efficiency of communication networks and data centres for the provision of digital services, and as a coefficient to apportion the total energy consumption of a network to a specific service. As energy efficiency becomes more important, energy intensity metrics are increasingly used to estimate the energy costs and benefits of changes in data volumes across networks and data centres. Typically, energy intensity integrates annual accounts of energy consumption and data transmitted. At shorter time scales, this metric is affected by the lack of correlation between transmitted data and energy consumption, which leads in some cases to inappropriate conclusions. In this work, we first review the use of energy efficiency metrics in the literature. Then, we define generic measures for energy efficiency as well as energy intensity. The relationships of those measures are analysed, and we show under which conditions they lead to the same or different results. Practical applications of the measures and their insights are demonstrated when benchmarking systems and when considering the value of the system's output. Furthermore, the limits and pitfalls of the metrics are analysed, especially considering the energy intensity metric for communication networks.

INDEX TERMS Energy intensity (EI), energy consumption (EC), energy efficiency (EE), output-related energy efficiency (OrEE), consumption-related energy efficiency (CrEE), communication networks, 6G.

I. INTRODUCTION

Energy efficiency (EE) metrics are mentioned in the context of system optimisation in standardization documents of the ITU-T [1], 3GPP [2], and ETSI [3]. One frequently used metric is the relation between the energy consumption and the data volume during some time period, which is given in J/bit, typically referred to as *energy intensity* (EI) [4], [5], [6], [7], [8], [9], [10], [11]. The less energy a given system consumes for some amount of data – or the more traffic is processed with the same amount of energy, the lower the EI. A smaller EI indicates that a system processes data *overall* more efficiently using less energy – or that a system is better utilized and processes more data.

Given that EI measures, i.e. concrete values of the EI metric, are specific to *a given system*, problems arise if they

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are used to evaluating scenarios of a *change* to that system. For example, energy intensity metrics cannot be used to reliably estimate the overall energy consumption of a future increase in data volumes transported by the same network.

A disregard for the constraints to the use of the EI metric has resulted in their misuse in the existing literature. This applies to both uses of energy intensity to estimate the impact of specific services, as well as those of entire networks. For example, [12] use EI to estimate energy consumption and carbon emissions from video conferencing by multiplying an assumed usage time with a mean service bitrate, and then estimate the reduction of network and data centre energy consumption and carbon emission from reducing the video conferencing data volumes by turning the video stream off. While mathematically plausible, a single EI value cannot consistently represent both the dynamics of power draw of the engineered system during operation as well as the environmental impacts on a whole-systems perspective. We will expand on the details in this article. An empirical observation that intermediate changes in network data volumes do not translate to network-level energy changes was given by GSMA when summarising the effects of additional traffic during the pandemic [13]. In this article, we will therefore answer the following research questions:

1) Is Energy Intensity (EI) a valid metric for energy efficiency (EE)? If yes, under which conditions?
2) Are the output-related EE metric and the consumption-related EE metric leading to the same conclusions?

The key contributions of this article are threefold. First, we will provide different *generic metrics for energy efficiency*, which are universally applicable in communication networks. We differentiate between the output-related energy efficiency (OrEE) and the energy consumption-related energy efficiency (CrEE) by comparing a system to an ideal system. Second, we *analyse the energy efficiency metrics* and show under which conditions they are identical, which is the case when using energy-proportional systems as ideal reference system. Furthermore, the relation to energy intensity is provided. Third, we provide *practical applications as well as limits* of those metrics. The analysis of the limits of EI as well as the relation towards energy efficiency are the key contributions of this article. We show how energy intensities can be properly utilized to quantify energy efficiency.

The remainder of this article is structured as follows. Section II revisits related work on energy intensity and energy efficiency and provides a classification of energy efficiency measures. The formal definitions of EI and EE measures are introduced in Section III, and then the relationships between EE metrics and EI are analysed in detail in Section IV. The practical applications and usage are demonstrated in Section V, before some practical limits are outlined. Finally, Section VI concludes this work with a summary of the main contributions.

II. RELATED WORK

In the following, energy intensity (Section II-A) and energy efficiency metrics (Section II-B) are reviewed. Measure refers to observed or monitored quantities in the communication network, while a metric is the generic concept to evaluate, in our case, the energy efficiency. We provide a classification of energy efficiency metrics (Section II-C) and focus on selected aspects (Section II-D).

A. ENERGY INTENSITY

Commonly, the EI of the Internet has been estimated for the different parts of the network: access, fixed edge, and core [4], [8], [9], [14], [15], and cellular networks [16], [17], as well as customer premise equipment (i.e. modems and WiFi routers) [8]. Less frequently, EI has also been calculated for server tasks, e.g., video streaming [18] and data centre storage [19]. The energy intensity of a device or a part of the network is the ratio between its total energy consumption (including cooling and power transformation, as well as signalling traffic between devices) and the data volume which is processed by the device or that part of the network. Network-level EI has been estimated from bottom-up [20] and top-down approaches [16]. Top-down models of the EI consider the overall energy demand of a part of a network (segment) and the total data traffic in that network (segment), see [6] and [8] for a discussion. In contrast, bottom-up models sum a device-level EI along average route lengths to estimate the network-level EI [7]. Besides a few exceptions (e.g., [21]), there is a general sparsity of real-world Internet service providers reporting of energy intensity.

Applications of EI include the apportioning of network energy consumption to a service for environmental reporting. For example, the GHG Protocol ICT sector guidance (a standard for carbon assessments for the ICT sector) [22] provides an EI constant to be used to convert data volume transported by a network to energy consumption for the purpose of carbon footprinting. This is deeply problematic for two reasons:

- EI of networks is not constant, as the energy efficiency of networking equipment increases rapidly through miniaturisation and other efficiency improvements in hardware and software.
- ICT infrastructure has a significant degree of non-proportional power draw, which means data traffic has a limited effect on the power draw of a network device.

Figure 1 shows energy consumption as a function of traffic, including a curve that describes the real system, as well as a single EI coefficient. When a single EI coefficient is used to evaluate a change of energy consumption for some change in data volume, the results significantly over-estimates the energy proportionality of the real system, and thus under-estimates the energy consumption in the real world. This undermines the benefits of EI for applications that aim to describe energy efficiency in the real world, particularly so, when changes in energy consumption are used to infer carbon impacts.

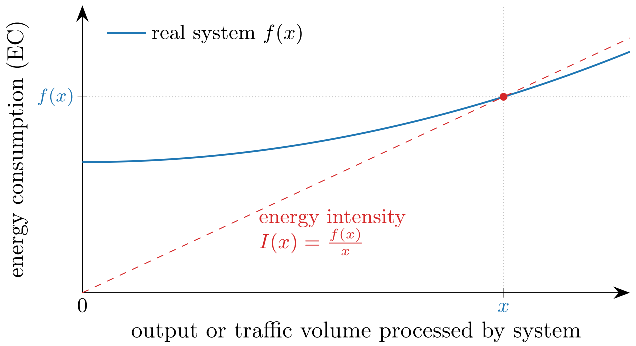

FIGURE 1. Two representations of energy consumption as a function of data volume. The blue curve describes the change of energy consumption as a function of traffic. As a network device is not fully proportional, the energy consumption is not zero even if traffic is zero. The energy intensity $I(x)$ is calculated for a specific combination of energy consumption $f(x)$ and traffic x. However, the single linear EI coefficient abstracts from the more complex function of energy consumption and traffic in the real system.

EI has also been used to estimate how energy consumption by telecommunications changes on a global scale over time. E.g., [23] extrapolate trend data of traffic growth and device efficiency improvements for fixed access networks, wireless access networks (2G, 3G, 4G, 5G) until 2030. The concrete values used in such estimates of EI are the subject of much debate. For example, [9] performs an in-depth analysis of estimates of the energy intensity and found inconsistencies in literature: "The main sources for these discrepancies lie in the inconsistent treatment of access networks and the inherent and converse biases of top-down and bottom-up modelling."

EI is also of high interest for cellular networks. E.g., [24] surveys related work on the energy use implications of 5G. Due to the traffic increase, significant improvements in the energy efficiency of mobile networks are required to limit the overall energy consumption. Thereby, the related work is often based on energy intensity values. Reference [25] uses projections for data volumes and actual figures for energy consumption of core networks and RANs used to establish energy intensity. Reference [26] show that "only a reduction of 5G network instant power consumption and, consequently, energy consumption, will contribute to the simultaneous improvement of both data and coverage EE [energy efficiency] metrics".

B. ENERGY EFFICIENCY METRICS

Surveys on energy efficiency metrics are typically relating to the definitions provided by standardization [1], [2], [3]. For example, [27] considers Internet energy efficiency metrics and revisits ITU-T Rec. L.1330 [28]. The energy efficiency is the ratio between the functional unit and the energy necessary to deliver the functional unit – and thus the inverse of EI. EE/EI can be calculated for different time scales: either instantaneously or over a certain time frame (typically one year). The instantaneous energy per bit considers the ratio of the instantaneous power to throughput. In contrast, the "energy per bit over a time frame" considers the ratio of energy consumption, consumed over a certain time frame, to the total traffic volume in the same time frame. We will consider the latter definition in this article. For the numerical results, we consider time frames longer than a day and thus being inclusive of the variability of traffic.

The state-of-the-art of energy efficiency in 5G networks was recently revisited in [29], referring to standards from ETSI, 3GPP, as well as ITU-T L.1331 [1], where different evaluation metrics were considered. Besides EI as an EE metric, they also provide a key performance indicator (KPI) that considers varying load levels and weighs resulting EI accordingly.

Other metrics of energy efficiency for mobile networks are the *Mobile Network Coverage Energy Efficiency*, which is the ratio between the area covered by the mobile network and the energy consumption when assessed during one year [3]. The unit is $\mathrm{m^2/J}$. The *latency-based EE metric* is the inverse of the product of the user plane latency and the energy consumption by the mobile network, which is expressed in $\mathrm{s^{-1}/J}$. Focusing on the wireless access link, the power efficiency of the wireless link may be quantified in bps/Hz/W, see also Figure 3.

An EE metric that is separate from EI is presented in [30]. They compare the maximum data volume possible to process per given amount of energy consumption. They then define a system's EE as the ratio between actual data volume and the potential data volume with the same energy consumption. We will consider this EE metric as output-related EE and relate it to average EI below. Another complementary definition of EE is provided in [31] and [32]. Here, the energy consumption of a system processing a certain traffic volume is considered. Then, the energy consumption of an ideal system is considered to process the same data volume. The energy efficiency is then the relation between the energy consumption of the ideal system and the real system. This consumption-related EE metric will also be considered in this article.

C. CLASSIFICATION OF ENERGY EFFICIENCY METRICS

The classification of metrics in literatures often considers the scope of the energy efficiency: *facility, network-level, equipment and devices, components*. A comprehensive overview and introduction is provided by [33] concluding that many metrics are quite close to each other, sometimes involving just a name change. The classification with respect to that scope considers how and where the measurements can be conducted to obtain the necessary inputs for that metrics. Reference [34] provides a division of the scope in categories. A facility requires energy for support (offices, lighting, security, Heating, Ventilation and Air Conditioning (HVAC)) and the IT consisting of Power Distribution System (PDS), Uninterruptible Power Supply (UPS), IT equipment (racks, application, storage, network server).

Another approach is presented by [35] differentiating between the *eco-design* and the *energy conservation*,

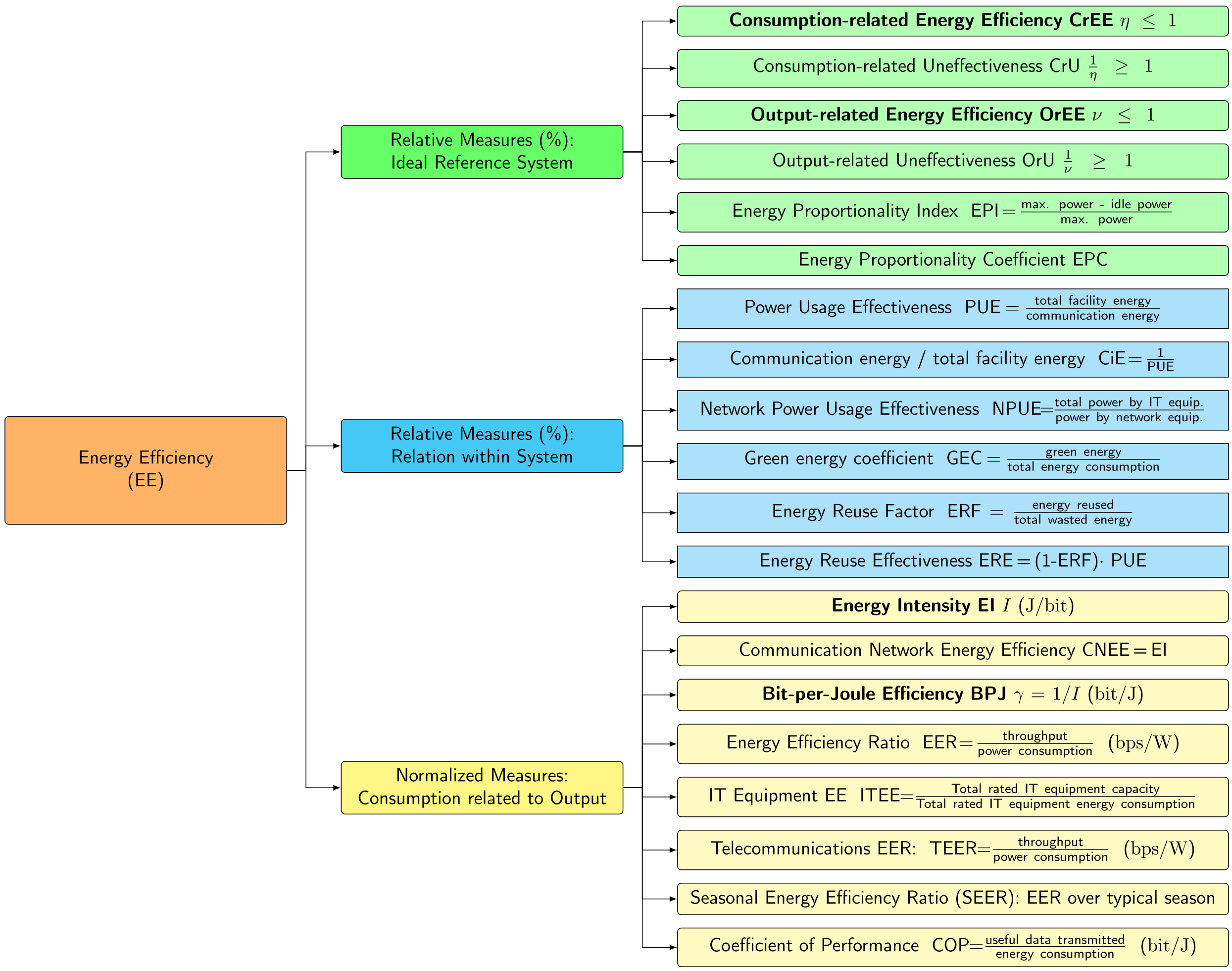

FIGURE 2. **Classification of existing energy efficiency measures and our proposed generic consumption- and output-related EE. The metrics in bold are analysed in detail in this article.**

whereby the focus is on data centres. In the context of communication networks, eco-design refers to the process of designing and optimizing network infrastructure, devices and systems to minimize their environmental impact throughout their lifecycle. Energy conservation in communication networks refers to the strategies, techniques, and technologies employed to reduce the energy consumption of network infrastructure and devices while maintaining or enhancing their performance. This is crucial for reducing operational expenses, minimizing environmental impact, and improving the overall sustainability of communication networks. Energy conservation focuses specifically on reducing energy usage and improving operational efficiency, whereas eco-design takes a holistic view of a product or system's entire lifecycle, aiming to minimize its overall environmental footprint. Both approaches are complementary and, when combined, can lead to significant improvements in sustainability and environmental performance. Their results show that the current evaluation metrics are focusing mainly on the assessment of energy saving of data centres, but for improving sustainability more comprehensive and multiscale evaluation metrics combining energy consumption, eco-design and other aspects including e.g., security are required.

In this article, we provide a *classification of energy efficiency measures* with respect to relative measures (unitless) and normalized measures, which relate the energy consumption to the output of the system, e.g. measured as overall traffic volume being processed. The relative measures can be differentiated whether an ideal system, e.g. an energy-proportional system, is used as reference or if another measure of the real system is used for comparison. Figure 2 shows our proposed taxonomy. The metrics in bold are thereby analysed in detail in this article. We focus on our generic definitions of output-related (OrEE) and consumption-related energy efficiency (CrEE), which are comparing a real system with an ideal reference system, and relate the two measures to energy intensity and bit-per-joule efficiency, which are quite common in

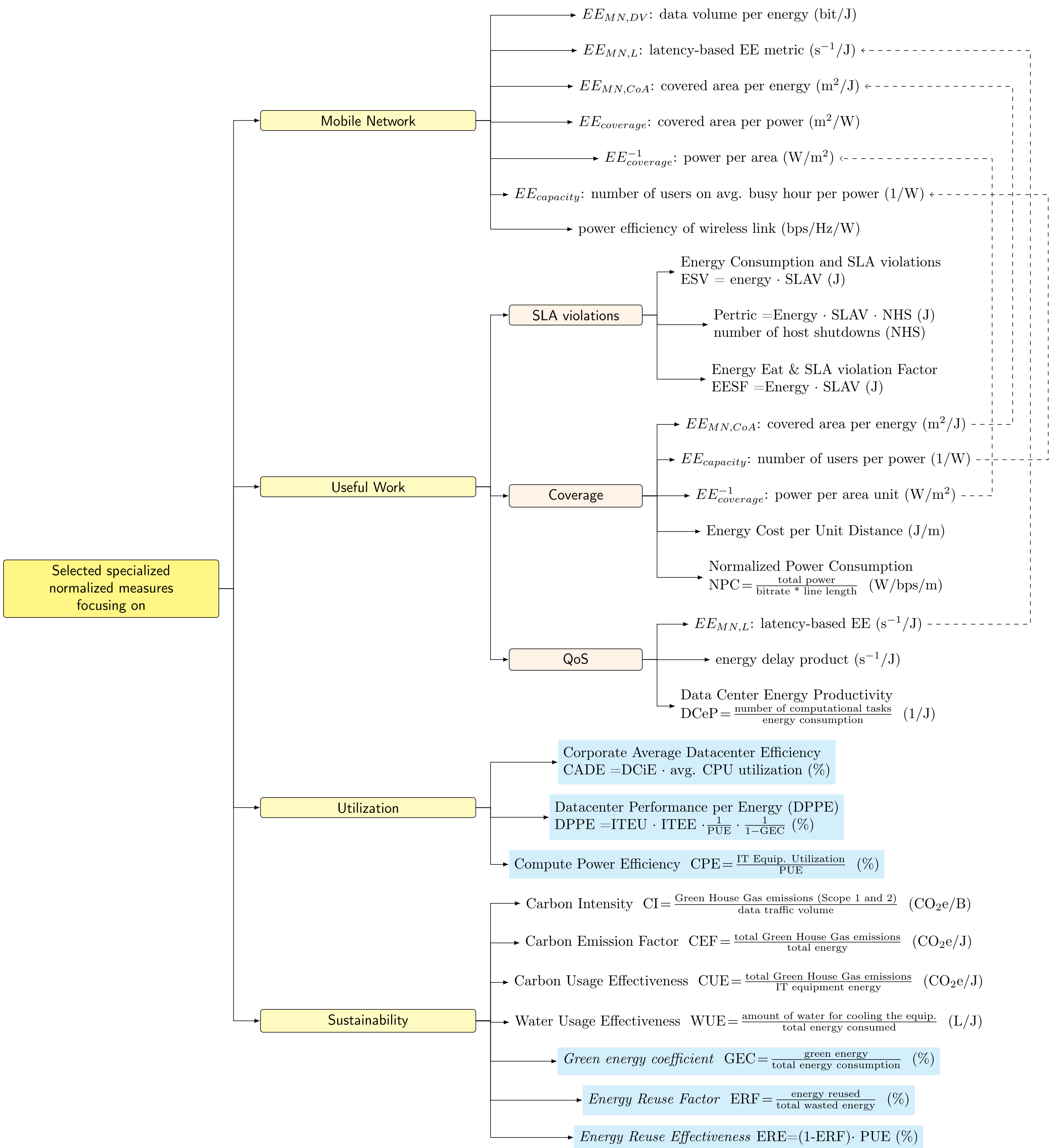

FIGURE 3. Several metrics are specialized in a particular domain or for a specific use case. Note that the metrics are normalized measures of energy consumption related to output. The metrics marked with *lightblue background color and in italics* are relative measures; all other metrics are normalized metrics relating energy consumption and output.

practice. The efficiency measures can also be expressed as (un-)effectiveness measures. The uneffectiveness is the inverse of the energy efficiency.

Other relative measures comparing to an ideal reference system are the energy proportionality index (EPI), which is analysed in Section IV-B. We show that EPI is a special case of our proposed OrEE and CrEE. The Energy Proportionality Coefficient (EPC) [36] has a different focus and quantifies the non-linear behaviour of systems. EPC considers the power consumption as a function of the network load or utilization and summarizes the entire curve, i.e. from idle to 100% utilization, into a single value by investigating the deviation from an energy-proportional ideal system, see [37].

The second class of energy efficiency measures considers a relation of energy consumption measures of the real system. A common measure is the Power Usage Effectiveness (PUE) [38], which compares the total facility energy consumption to the energy consumed specifically by the IT equipment. In the context of communication networks, we may consider the ratio of the total energy consumption of a facility and the energy consumption of devices used for communication networks. Similarly, Data Center infrastructure Efficiency (DCiE) is a metric used to measure the energy efficiency of a data centre by calculating the ratio of the energy consumed by IT equipment to the total energy consumed by the entire data centre. Thus, DCiE is the inverse of PUE. In the context of communication networks, we may again consider the energy consumption related to the communication network, referred to as CiE in Figure 2. Thereby, it is quite common to differentiate the energy consumption of the facility, e.g. including cooling, and the energy consumption of the IT equipment only. Consequently, Network Power Usage Effectiveness (NPU) relates then the total power by IT equipment to the power by the network equipment. Another relevant relative measure for sustainable networking beyond energy efficiency is the Green Energy Coefficient (GEC) which quantifies the percentage of energy from certified green sources. Energy Reuse Factor (ERF) is a metric used to evaluate the efficiency of energy reuse in data centres. It measures how effectively a data centre can capture and reuse waste energy (typically heat) generated by its operations. ERF is the ratio of reused energy to the total amount of wasted energy. A related measure is the Energy Reuse Effectiveness (ERE) [39] which is the total energy consumption without the reused energy in relation to the IT energy. Reference [39] provides the following definitions.

$$\begin{aligned}\text{PUE} &= \frac{\text{total energy}}{\text{IT energy}} \\ &= \frac{\text{cooling + power + lighting + IT energy}}{\text{IT energy}} \\ \text{ERF} &= \frac{\text{reuse energy}}{\text{total energy}} \\ \text{ERE} &= \frac{\text{cooling + power + lighting + IT - reuse energy}}{\text{IT energy}} \\ &= (1 - \text{ERF}) \cdot \text{PUE}\end{aligned}$$

The third class of energy efficiency measures relates the energy consumption to the output of the system. The key measures are the energy intensity (EI) as ratio between energy consumption and total traffic volume, as well as the bit-per-joule efficiency as the inverse of the EI. The energy intensity is also referred to as Communication Network Energy Efficiency (CNEE) [37] to highlight the energy consumed by the network equipment. To be more precise, EI is more general and may consider the energy consumption and the traffic volume for an arbitrary system or subsystem, e.g. dedicated to a certain application or dedicated to parts of the network. The Energy Efficiency Ratio (EER) considers the ratio of throughput and power consumption, which is identical to the bit-per-joule efficiency, see Section V-C5. The Telecommunications Energy Efficiency Ratio (TEER) [28] emphasizes the consideration of telecommunications equipment. TEER is calculated as the ratio of the total data throughput to the total energy consumed by the telecommunications equipment over a specific period. Thereby, the Seasonal Energy Efficiency Ratio (SEER) focuses on the EER over a typical season. The IT Equipment Energy Efficiency (ITEE) [40] is the total rated capacity of the IT equipment over its total rated power consumption. One important measure is the coefficient of performance (COP) which is basically the bit-per-joule efficiency. However, COP considers the useful data transmitted and therefore takes into account to some degree the value of the output of the communication network, which we analyse in Section V-B.

D. SELECTED MEASURES: USEFUL WORK, UTILIZATION, SUSTAINABILITY

Specific measures on energy efficiency are introduced in the literature. The intention is often to provide single metrics which guide the operation and optimization of systems. Thereby, key aspects are the consideration of useful work, the utilization of systems, or sustainability. Furthermore, particular networks like mobile networks allow the definition of appropriate metrics. Thereby, the output of the system may include other measures like coverage, utilization, SLA violations, but also the consideration of useful data transmitted instead of overall traffic volume. Figure 3 visualizes selected metrics, which we briefly discuss in the following.

First, *useful work* is considered. However, the usefulness of work strongly depends on the concrete use case and the system under investigation. Service-Level Agreements (SLAs) and in particular their Violations (SLAV) are of practical importance. Reference [41] reviews some SLA-driven energy-related metrics. The Energy Consumption and SLA Violations (ESV) metric is the product of both measures. In practice, a system aims at minimizing both measures and hence the product ESV. EESF considers the Energy Eat by Servers and Switches (EESS) and formulates the Energy Eat and SLA violation Factor as product of EESS and SLA violations. Hence, ESV and EESF are very similar, just with a different focus on what is considered in the energy consumption. Pertric (*Per*formance Me*tric*) [42] additionally takes the number of host shutdowns into account. The objective of this metric is to maximize overall performance while minimizing energy consumption, average SLA violations, and the number of host reactivations.

Useful work may consider the QoS directly, not only SLA violations. We already discussed the *latency-based EE* *metric* [3] as the inverse of the product of the user plane latency and the energy consumption by the mobile network, which is expressed in s^{-1}/J. Similarly, [43] combines the energy consumption and the delay through the Energy-Delay Product (EDP). Hence, the useful work considers the latency of the communication network. In the context of data centres, the Data Center energy Productivity (DCeP) measures the ratio of the number of computational tasks and the energy consumption. The DCeP is therefore a *productivity metric* that measures the ratio of useful work done to its total energy consumption. In the context of communication networks, we may consider the ratio of the amount of useful data transmitted and the energy consumption, which is the Coefficient of Performance (COP).

Another aspect of useful work considers the coverage of mobile networks as output of the system. To this end, the ratio of covered area to energy consumption or power consumption may be considered. The inverse ratio is then the energy consumption or power consumption per area unit. The coverage may be expressed by the number of users who are served during an average busy hour. Then the ratio of the number of users and power consumption quantifies the power consumption in relation to useful work by the system. For wired networks, the distance may be considered which is traversed by the system. Then, a normalized metric is the energy consumption per unit distance. The normalized power consumption (NPC) [3] additionally considers the bitrate of the system and is an indicator for the amount of power required to transport 1 Mbps of data over a distance of 1 km. The idea of NPC is to enable the comparison of different technologies regarding the energy efficiency of transporting information. The metrics related to mobile networks are additionally included in Figure 3. The link between those metrics and their interpretation as useful work metrics regarding coverage or QoS is visualized by a dashed arrow.

Second, the *utilization* of the system is considered in the definition of normalized measures. The Corporate Average Datacenter Efficiency (CADE) is the product of $\text{DCiE} = \frac{1}{\text{PUE}}$ and the average CPU utilization in a data centre [44].

$$\text{CADE} = \frac{\text{avg. CPU utilization}}{\text{PUE}}$$

The Datacenter Performance per Energy (DPPE) considers several aspects. The IT Equipment Utilization (ITEU) quantifies the degree to which IT equipment is in operation. The ITEU value is 0 if no IT equipment is operating. If the IT equipment is fully in operation (100% utilized), the ITEU value is 1. The IT Equipment Energy Efficiency (ITEE) quantifies the degree of potential energy savings installed in a data centre. The larger ITEE the more energy saving is introduced in the system. DPPE is the product of the IT Equipment Utilization (ITEU), IT Equipment Energy Efficiency (ITEE), the inverse of the Power Usage Effectiveness (PUE), and inverse of the Non-Green Energy Coefficient (1)-GEC).

$$\text{DPPE} = \text{ITEU} \cdot \text{ITEE} \cdot \frac{1}{\text{PUE}} \cdot \frac{1}{1 - \text{GEC}}$$

The Compute Power Efficiency (CPE) is the ratio of the percentage of power consumed by IT equipment (DCiE) and the ITEU, i.e., the utilization of the IT equipment.

$$\text{CPE} = \frac{\text{ITEU}}{\text{PUE}} = \text{ITEU} \cdot \text{DCiE}$$

Third, *sustainability* advances energy efficiency by integrating additional sustainability aspects, like usage of green energy, reuse of wasted energy, water and material usage, and so on, and by advancing the energy conservation ('Reduce') to 'Reuse' and 'Recycling'. Thus, the three 'R's of sustainability (reduce, reuse, recycle) are reflected by those metrics. We already discussed the green energy coefficient (GEC), the energy reuse factor (ERF), and the energy reuse effectiveness (ERE) in Section II-C. An overview of energy efficiency metrics concerning sustainability is provided in [41].

Instead of energy intensity, the carbon intensity is the ratio of the green house gas (GHG) emissions (CO_2e) and the energy consumption. Thereby, typically, scope 1 and scope 2 emissions are considered. Scope 1 emissions are direct GHG emissions from sources that are owned or controlled by the organization operating the system. Scope 2 emissions are indirect GHG emissions associated with the consumption of purchased electricity, steam, heating, and cooling. These emissions occur at the facility where the energy is generated, but are attributed to the organization that consumes the energy. Note that scope 3 emissions are typically not considered, which are all other indirect emissions that occur in the value chain of the operator of a system. The Carbon Emission Factor (CEF) is a generic measure which relates the GHG emissions to the total energy consumption. Carbon Usage Effectiveness (CUE) is inspired from PUE and quantifies the ratio of GHG emissions and energy consumption of the IT equipment. Similarly, Water Usage Effectiveness (WUE) is the ratio of the amount of water for cooling the equipment to the total energy consumed and used in the context of data centres.

III. FORMAL DEFINITIONS OF ENERGY EFFICIENCY (EE) AND ENERGY INTENSITY (EI)

A. NOTION OF A SYSTEM

We consider a communication system for some time, during which a certain amount of traffic volume x is processed and an amount of energy $f(x)$ is consumed. The system's behaviour regarding the energy consumption is described by the function $f(x)$, depending on the traffic volume x. This processed traffic volume represents the output or the work by the communication system, e.g. the traffic volume x processed by a radio access network which requires a certain amount of energy $f(x)$. In other words, $f(x)$ is the *system function of the real system*, that characterizes the system and

TABLE 1. Notation of variables and metrics.

variable	explanation [standard unit]
x	traffic volume in the real system [bit]
$f(x)$	real system function: energy consumption for traffic volume x of the real system [J or W s]
$h(x)$	ideal system function: optimal energy consumption for traffic volume x of an ideal system [J]
x^*	traffic volume of an ideal system with energy consumption $f(x)$ [bit]
$I(x)$	energy intensity (EI) of the real system for traffic volume x and energy consumption $f(x)$ [J/bit]
I_y	energy intensity (EI) of the system in year y [J/bit]
$\gamma(x)$	bit-per-joule efficiency [bit/J]
$\eta(x)$	energy consumption-related EE metric [J/J=1]
$\nu(x)$	output-related EE metric [bit/bit=1]

describes the output of a system (traffic volume) in response to a given input (energy consumption).

Definition 1 (System Function of a Communication System): The system function $f(x)$ characterizes the processed traffic volume x in response to the required energy consumption $f(x)$ of a communication system.

Instead of the traffic volume, we may also consider the traffic load ρ of the system, which is then the ratio between the processed traffic volume x and the theoretical maximum $x_{\max}$, i.e. $\rho = x/x_{\max}$. However, for the sake of readability, we consider the traffic volume, since energy intensity is typically given in J/bit and the relationships in Section IV consider traffic volume.

B. EFFICIENCY OF A SYSTEM

In general, efficiency signifies the level of performance that uses the least amount of input to achieve the highest amount of output. Thus, efficiency is a measurable concept, quantitatively determined by *the ratio of useful output to total useful input*. In our context of energy efficiency, we therefore may consider the amount of useful output (the traffic volume x) produced per the amount of resources consumed (the energy consumption $f(x)$). This definition directly leads to a normalized measured $\gamma(x)$ of energy consumption to quantify energy efficiency (Section III-C). It is inversely proportional to energy intensity.

As an alternative, efficiency is often expressed as *percentage of the result that could ideally be expected*. Therefore, efficiency is defined by comparing a real system with an ideal system. This consideration leads to the energy consumption-related EE (Section III-D) and output-related EE metric (Section III-E).

C. BIT-PER-JOULE EFFICIENCY AND ENERGY INTENSITY OF THE SYSTEM

The energy intensity $I(x)$ is the ratio of the energy consumption $f(x)$ and the traffic volume x over the same time frame. The basic unit of the EI is J/bit.

Definition 2 (Energy Intensity): The energy intensity (EI) of a system with system function $f(x)$ is the ratio of the energy consumption $f(x)$ and the traffic volume x processed by the system over the same time frame.

$$I(x) = \frac{f(x)}{x} \tag{1}$$

We may also define the *bit-per-joule efficiency* considering the inverse ratio.

Definition 3 (Bit-Per-Joule Efficiency): The bit-per-joule efficiency of a system with system function $f(x)$ is the ratio of the traffic volume x and the energy consumption $f(x)$ over the same time frame.

$$\gamma(x) = \frac{1}{I(x)} = \frac{x}{f(x)} \tag{2}$$

With a given energy intensity $I(x)$ for a certain time frame during which the traffic volume x was processed, the energy consumption can be derived exactly. Note that the EI and the traffic volume are aligned – which is an important requirement, as we will see later. By the definition of the EI, the following trivial relationship is obtained, where $I(x)$ denotes the energy intensity for a certain time frame and x denotes the traffic volume in that time frame. The energy consumption $f(x)$ during that time frame is derived as

$$f(x) = I(x) \cdot x. \tag{3}$$

Figure 1 visualizes the system's energy consumption $f(x)$ depending on the traffic volume x processed by the system (i.e. the output). Please note that the EI of the system, when $f(x)$ and x are measured over a certain amount of time, is therefore simply the gradient of the linear curve through the point of origin (dashed red curve). This linear function is therefore $g(\xi) = I(x) \cdot \xi = \frac{f(x)}{x} \cdot \xi$. Therefore, if $\xi = x$, then $g(x) = f(x)$; however, for other points $\xi \neq x$, $g(x) \neq f(x)$ in general.

When energy intensities are provided, often, a time frame of one year is considered. The total traffic volume in a year y is denoted as $V(y)$. The corresponding energy intensity in year y is then I_y with $x \stackrel{\text{def}}{=} V(y)$.

$$I_y = \frac{f(V(y))}{V(y)} = \frac{f(x)}{x} \tag{4}$$

D. ENERGY CONSUMPTION-RELATED ENERGY EFFICIENCY METRIC

The following two energy efficiency metrics from literature are relating the quantities to that of an ideal system. As a result, normalized values between 0 and 1 are obtained. Thereby, 1 indicates that a system obtains the same energy efficiency as the ideal system.

The *EC-related energy efficiency metric* [31] considers $f(x)$ and x. An ideal system would require, however, only $h(x)$ of energy with $0 \leq h(x) \leq f(x)$. Then, the energy efficiency is defined as follows and bounded in the interval [0; 1].

Definition 4 (Consumption-Related Energy Efficiency): The energy consumption-related energy efficiency $\eta(x)$ relates the energy consumption $h(x)$ of an ideal system as reference and the energy consumption $f(x)$ of a real system *with system function $f(x) \geq h(x)$.*

$$\eta(x) = \frac{h(x)}{f(x)} \tag{5}$$

If the real system is the ideal system, i.e. $f(x) = h(x)$, the maximum energy efficiency is reached and it is $\eta(x) = 1$. The higher the energy consumption of a real system, the smaller the energy efficiency.

E. OUTPUT-RELATED ENERGY EFFICIENCY METRIC

Similarly, the *output-related energy efficiency metric* [30] considers the energy consumption $f(x)$ of a system for processing the traffic volume x. An ideal system would process, however, a traffic volume x^* with the same EC $f(x)$. Then, we may define energy efficiency as follows.

Definition 5 (Output-Related Energy Efficiency): The output-related energy efficiency $\nu(x)$ relates the traffic volume x processed by a real system with energy consumption $f(x)$ to the maximum traffic volume x^* that can be processed by an ideal system with the same energy consumption $h(x^*) = f(x)$.

$$\nu(x) = \frac{x}{x^*} = \frac{x}{h^{-1}(f(x))} \tag{6}$$

The inverse function $h^{-1}(y)$ provides the amount of traffic that the ideal system can process with an amount of energy y. Thus, $h^{-1}(f(x))$ yields the traffic volume for the energy consumption $f(x)$ of the real system with $x^* \geq x$. Therefore, $\nu(x)$ is bounded in the interval [0; 1]. If the real system is the ideal system, i.e. $f(x) = h(x)$, then $h^{-1}(h(x)) = x$ and the maximum energy efficiency is reached, i.e. $\nu(x) = 1$.

Figure 4 visualizes both measures of EE which are based on the comparison to a real system $f(x)$. Considering the point $(x, f(x))$, there are two options to compare with the ideal system. Either the horizontal line through the point $(x^*, f(x))$ yielding $\nu(x)$ or the vertical line through the point $(x, h(x))$ yielding $\eta(x)$.

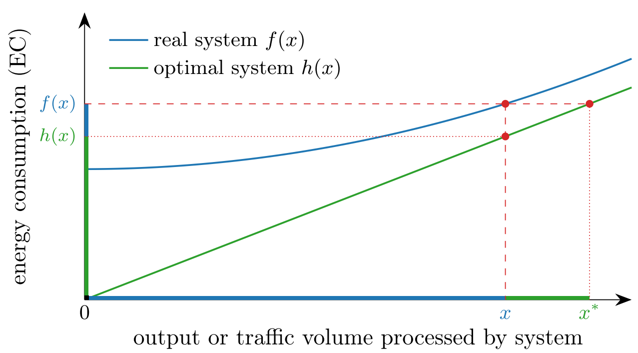

FIGURE 4. Definition of output-related energy efficiency $\nu(x) = x/x^*$ as ratio between conducted work x of the real system and the potentially conducted work x^* of the optimal system. Similarly, the consumption-related energy efficiency $\eta(x) = h(x)/f(x)$ reflects the ratio of the energy consumption $h(x)$ of the optimal system to the energy consumption $f(x)$ of the real system.

F. IDEAL SYSTEM AND ENERGY-PROPORTIONAL SYSTEM

The calculation of the EC- and output-related EE metrics requires an ideal system for comparison. Based on the notion of systems in this work, the ideal system is characterized by a function $h(x)$ of the energy consumption depending on the output or traffic volume processed by the ideal system. However, the question arises how the ideal system's function $h(x)$ looks like.

For a given real system and the real system function $f(x)$, we may derive directly the ideal system function $h(x)$. Thereby, we assume an *energy-proportional system* as an ideal system, where the energy usage $h(x)$ of the system scales proportionally with its workload x. This means that the energy consumption of the system closely aligns with the amount of traffic it is processing at any given time. An energy-proportional system consumes no energy when idle, and its energy consumption increases linearly as the amount of traffic increases. The ideal system function is therefore a linear function with slope m but without any offsets, i.e. a linear function through the origin.

Definition 6 (Energy-Proportional System): The energy consumption $h(x)$ of the system scales proportionally with the traffic volume x processed by the system. The constant slope $m > 0$ reflects the energy intensity of the energy-proportional system $I(x) = h(x)/x = m$.

$$h(x) = m \cdot x \tag{7}$$

The slope m can be derived from the real system function $f(x)$ by identifying the smallest gradient of the system, i.e., $m = \min_{\xi \geq 0} \frac{f(\xi)}{\xi}$. This ensures that $h(x) \leq f(x)$ for any x.

$$h(x) = m \cdot x = \min_{\xi \geq 0} \frac{f(\xi)}{\xi} \cdot x = \min_{\xi \geq 0} I(\xi) \cdot x \tag{8}$$

Energy proportionality was first discussed in the context of computing servers [45] and later extended to network equipment [46]. Energy-proportional systems are highly efficient not just under maximum load but across various workload conditions. This contrasts with traditional systems, where energy consumption may be high even when the system is not fully utilized. Thus, it may be impossible to engineer that ideal system in practice, but it reflects the theoretical optimum and is therefore useful to quantify EE. For example, the system has a minimum amount of energy consumption in idle mode, i.e. if not processing any data. This may be realistic in order to have a responsive system waiting for incoming requests to process them. Based on such expert knowledge of the system or by appropriate means, e.g. optimization theory, the function $h(x)$ may be derived. In that case, a linear function with offset $c > 0$ and slope m' may be appropriate $h(x) = m'x + c$.

Definition 7 (Linear System Model): The energy consumption $h(x)$ of the system is a linear function of the traffic volume x processed by the system with constants $m > 0$ and $c \geq 0$.

$$h(x) = m \cdot x + c \tag{9}$$

Research on energy-efficient systems often aims at approaching such energy-proportional systems. A significant focus is on reducing the power usage when the system is idle. It is a 6G power consumption goal to enable zero-energy consumption [47], when there is no traffic at a base station, e.g., by switching off a cell. Thus, energy-proportional systems (with $c = 0$) are a design goal in 6G.

G. ENERGY CONSUMPTION VS. POWER CONSUMPTION

The system function of the real system $f(x)$ considers the energy consumption and the processed traffic volume over a dedicated time interval Δt. To get reasonable results in practice, the time interval must be long enough to take into account the system's variability, since the traffic arrivals to the system are a stochastic process. If Δt is sufficiently long, the system conditions are varying slowly enough such that the system acts over that period of time as in equilibrium. Thus, the traffic rate $\bar{x} = x/\Delta t$ and the average power consumption $\bar{f}(x) = f(x)/\Delta t$ are quasi constant. This is referred to as a quasi-stationary system. Similarly, for the ideal system, we observe $\bar{h}(x) = h(x)/\Delta t$.

For the energy intensity and the energy efficiency metrics, it does not matter if the system function considers i) the energy consumption depending on the traffic volume or ii) the power consumption depending on the traffic rate during the time Δt. To this end, we define the following variations of the system function depending on whether the traffic volume x or the traffic rate $\bar{x}$ is used.

- $f(x)$ energy consumption $f(x)$ [J] depending on traffic volume x [bit]
- $\bar{f}(x)$ power consumption $\bar{f}(x)$ [W] depending on traffic volume x [bit]
- $\tilde{f}(\bar{x})$ energy consumption $\tilde{f}(\bar{x})$ [J] depending on traffic rate $\bar{x}$ [bit/s]
- $\hat{f}(\bar{x})$ power consumption $\hat{f}(\bar{x})$ [W] depending on traffic rate $\bar{x}$ [bit/s]

Thus, we have the following system functions and their relation to $f(x)$ and traffic rate $\bar{x} = x/\Delta t$.

$$\bar{f}(x) = f(x)/\Delta t \tag{10}$$

$$\tilde{f}(\bar{x}) = f(\bar{x}\cdot\Delta t) \tag{11}$$

$$\hat{f}(\bar{x}) = f(\bar{x}\cdot\Delta t)/\Delta t \tag{12}$$

Similarly, the ideal system can be derived by such system functions. The inverse system functions are then as follows, depending on whether the energy consumption y or the power consumption $\bar{y} = y/\Delta t$ is given.

$$\bar{h}(x) = h(x)/\Delta t \qquad x = \bar{h}^{-1}(\bar{y}) = h^{-1}(\bar{y}\cdot\Delta t) \tag{13}$$

$$\tilde{h}(\bar{x}) = h(\bar{x}\cdot\Delta t) \qquad \bar{x} = \tilde{h}^{-1}(y) = h^{-1}(y)/\Delta t \tag{14}$$

$$\hat{h}(\bar{x}) = h(\bar{x}\cdot\Delta t)/\Delta t \qquad \bar{x} = \hat{h}^{-1}(\bar{y}) = h^{-1}(\bar{y}\cdot\Delta t)/\Delta t \tag{15}$$

The energy intensity is then as follows. Thus, it does not matter if i) the energy consumption and traffic volume or ii) the power consumption and traffic rate are used.

$$I(x) = \frac{f(x)}{x} = \frac{f(\bar{x}\cdot\Delta t)}{\bar{x}\cdot\Delta t} = \frac{\hat{f}(\bar{x})}{\bar{x}} \tag{16}$$

$$I(x) = \frac{f(x)}{x} = \frac{\bar{f}(x)\cdot\Delta t}{x} = \frac{\bar{f}(x)}{\bar{x}} \tag{17}$$

For the consumption-related energy efficiency, we obtain the following relationships. Thus, the EE is derived by using the same representation of the system function for the real and the ideal system.

$$\eta(x) = \frac{h(x)}{f(x)} = \frac{h(x)/\Delta t}{f(x)/\Delta t} = \frac{\bar{f}(x)}{\bar{h}(x)} \tag{18}$$

$$\eta(x) = \frac{h(x)}{f(x)} = \frac{h(\bar{x}\cdot\Delta t)}{f(\bar{x}\cdot\Delta t)} = \frac{\tilde{h}(\bar{x})}{\tilde{f}(\bar{x})} \tag{19}$$

$$\eta(x) = \frac{h(x)}{f(x)} = \frac{h(\bar{x}\cdot\Delta t)/\Delta t}{f(\bar{x}\cdot\Delta t)/\Delta t} = \frac{\hat{h}(\bar{x})}{\hat{f}(\bar{x})} \tag{20}$$

For the output-related energy efficiency, we observe a similar result. If the same representations of the system functions are used, we obtain $\nu(x)$.

$$\nu(x) = \frac{x}{h^{-1}(f(x))} = \frac{x}{h^{-1}(\bar{f}(x)\cdot\Delta t)} = \frac{x}{\bar{h}^{-1}(\bar{f}(x))} \tag{21}$$

$$\begin{aligned}\nu(x) &= \frac{x}{h^{-1}(f(x))} = \frac{\bar{x}\cdot\Delta t}{h^{-1}(f(\bar{x}\cdot\Delta t))}\\ &= \frac{\bar{x}}{h^{-1}(\tilde{f}(\bar{x}))/\Delta t} = \frac{\bar{x}}{\tilde{h}^{-1}(\tilde{f}(\bar{x}))}\end{aligned} \tag{22}$$

$$\begin{aligned}\nu(x) &= \frac{x}{h^{-1}(f(x))} = \frac{\bar{x}\cdot\Delta t}{h^{-1}(f(\bar{x}\cdot\Delta t))}\\ &= \frac{\bar{x}}{h^{-1}(\hat{f}(\bar{x})\cdot\Delta t))/\Delta t} = \frac{\bar{x}}{\hat{h}^{-1}(\hat{f}(\bar{x}))}\end{aligned} \tag{23}$$

Theorem 1 (System Function Representation): For the computation of the consumption- and output-related energy efficiency metrics, the same system function representations of the real and ideal system must be used. The system function represents either the energy consumption or the power consumption as a function of the traffic volume or the traffic rate. To compute energy intensity and the bit-per-joule efficiency, either i) energy consumption and traffic volume or ii) power consumption and traffic rate may be used.

For the sake of simplicity, we use in the following $f(x)$ to represent the system function as energy consumption per traffic volume or power consumption per traffic rate.

IV. RELATIONSHIPS BETWEEN ENERGY EFFICIENCY METRICS AND ENERGY INTENSITY

Before we analyse the relationships between the different energy efficiency measures, we consider the power consumption of 5G-Advanced base stations as an illustrative example for those measures (Section IV-A). Then, we derive the energy efficiency measures when using energy-proportional systems as reference, which brings important guidelines for practice (Section IV-B). The impact of constant offsets is further analysed for ideal linear systems (Section IV-C) and ideal general systems with offsets (Section IV-D). Finally, general inequalities for the EC-related and output-related EE are provided (Section IV-E).

A. EXAMPLE: POWER CONSUMPTION OF 5G-ADVANCED BSS

For illustrating the different metrics, we consider now the power consumption for 5G-Advanced base stations (BSs). Based on measurements, a linear device power model [27] is found for such a 5G-Advanced BS [48], [49]. Thereby, a certain amount of power in idle mode is consumed, even when not processing any data. The measurements reveal the parameters of the linear model, slope α and constant offset β. To be more precise, the model provides the power consumption $f(x)$ depending on the traffic rate x for $x \leq$ 500 Mbps.

$$f(x) = \alpha \cdot x + \beta \tag{24}$$

Figure 5 shows the power consumption (in kW) depending on the traffic rate (in Mbps). Thus, when the BS is observed for a time frame Δt and a traffic rate x is measured, the energy consumption is $f(x) \cdot \Delta t$ and the overall traffic volume is $x \cdot \Delta t$. Then, the EI $I(x)$ and the bit-per-joule efficiency $\gamma(x)$ are as follows. Hence, it does not matter if the energy consumption and the traffic volume or the power consumption and traffic rate are considered.

$$I(x) = \frac{f(x) \cdot \Delta t}{x \cdot \Delta t} = \frac{f(x)}{x} \tag{25}$$

$$\gamma(x) = I(x)^{-1} = \frac{x}{f(x)} \tag{26}$$

For computing, the EC- and output-related EE, the ideal system as reference is provided. The energy-proportional ideal system (EIS) is characterized by

$$h(x) = \frac{f(x_{\max})}{x_{\max}} \cdot x = \frac{\alpha x_{\max} + \beta}{x_{\max}} \cdot x, \tag{27}$$

since the minimum energy intensity is reached for the maximum utilization of the BS at $x_{\max} = 500$ Mbps, resulting in the slope $m = \alpha + \frac{\beta}{x_{\max}}$ of the energy-proportional system function.

However, the idle power consumption of a realistically optimal system (ROS) is assumed to be half of the real system's power consumption. Therefore, we assume another system function $g(x)$ for comparing the real system with.

$$g(x) = \frac{\alpha x_{\max} + \frac{\beta}{2}}{x_{\max}} \cdot x + \frac{\beta}{2} \tag{28}$$

Figure 6 provides the bit-per joule efficiency. The energy-proportional system takes a constant value independent of the traffic rate, which is the key property of the ideal system. However, the absolute value is difficult to interpret, since the measure is not scaled in the range [0;1]. For the real system and the realistically optimal system, the bit-per-joule efficiency approaches γ_h, i.e. the constant bit-per-joule efficiency of the energy-proportional system, for larger traffic rates.

$$\gamma_h(x) = \frac{x_{\max}}{\alpha x_{\max} + \beta} \tag{29}$$

Figure 7 shows the energy efficiency ν and η for the real system depending on the energy-proportional (ν_h, η_h) and the realistically optimal system (ν_g, η_g), respectively. *First*, we observe that the EC-related (η_g) and the output-related EE (ν_g) lead to different absolute values if the realistically optimal system (g) is used as reference. Especially, if the system is idle, the output-related EE indicates the worst EE, $\nu_g(0) = 0$. For the sake of readability, units are not provided in the following. The real system is not providing any output, but the energy consumption $f(0) = \beta$ is just for powering the device in idle mode. However, the realistically optimal system requires only $g(0) = \frac{\beta}{2}$ in idle mode. Hence, the remaining power $f(0) - g(0) = \frac{\beta}{2}$ can be used for processing some traffic in the ROS. Therefore, the output-related EE is $\nu_g(0) = 0$. This example demonstrates nicely the meaning of this output-related EE metric, which focuses on how much output is generated by a system in comparison to the output of the ideal system.

In contrast, the EC-related energy efficiency yields a value of $\eta_g(0) = \frac{1}{2}$. The interpretation of this measure is that for the traffic rate $x = 0$, the ROS system requires only half of the EC of the real system. With the ROS assumed to be the ideal system in the quantification of the EC-related energy efficiency, it is not relevant how much traffic x is processed, but only the real and the theoretically optimal EC of the system is considered.

Second, we observe that the output-related EE is always less than the EC-related EC, i.e. $\nu_g(x) \leq \eta_g(x)$ for any x. In Section IV-E, we will investigate under which conditions this inequality holds.

Third, the EC- and output-related EE metrics are identical, when the energy-proportional system is used to compare the real system with an ideal system. The comparison with the energy-proportional ideal system is investigated in general in Section IV-B.

B. RELATIONSHIPS FOR ENERGY-PROPORTIONAL IDEAL SYSTEMS

As introduced in Section III-F, energy proportionality refers to the property of a system or device to consume energy in direct proportion to its workload or utilization level. A communication system is considered energy-proportional when its energy consumption scales up or down based on the traffic volume it is processing. An ideal system is an energy-proportional system.

The ideal system function $h(x)$ is therefore

$$h(x) = m \cdot x \tag{30}$$

for the traffic volume x and a constant $m > 0$ characterizing the EIS. This constant $m = h(x)/x$ reflects the energy intensity of the EIS.

The output- and EC-related energy efficiency metrics of the real system are now computed using the corresponding system function $f(x)$. The volume x^* that could have been processed by the ideal system for a given energy consumption

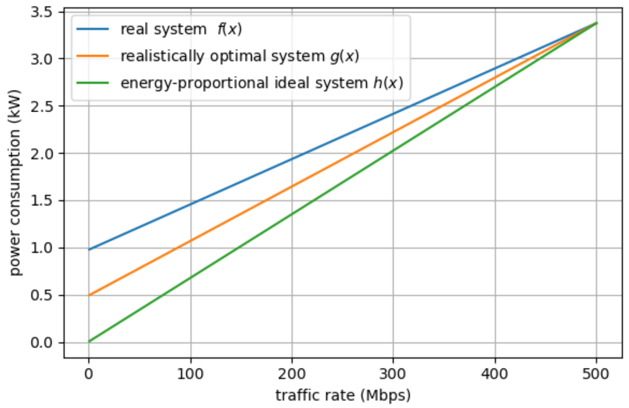

FIGURE 5. Power consumption $f(x)$ for 5G-Advanced base stations (BSs) modelled as linear device power model [27] with parameters taken from [48], [49]. A perfect ideal system $h(x)$ and a more realistically optimal system $g(x)$ are used for quantifying energy efficiency.

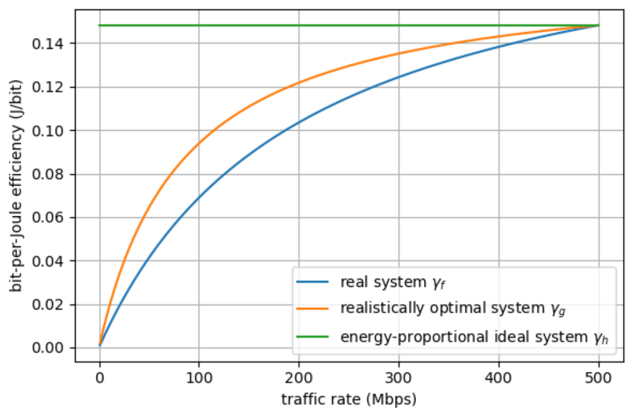

FIGURE 6. Bit-per-joule efficiency for the 5G-Advanced BSs (γ_f) and the assumed energy-proportional ideal system (γ_h) as well as the realistically optimal system (γ_g).

y is the inverse function $h^{-1}(y) = \frac{y}{m}$. The real system consumes $f(x)$ for the traffic x, thus, $x^* = \frac{f(x)}{m}$. We obtain the following output-related EE $\nu(x)$.

$$\nu(x) = \frac{x}{x^*} = \frac{x}{h^{-1}(f(x))} = \frac{mx}{f(x)} \tag{31}$$

The EC-related energy efficiency is the relation between the EC of the ideal and the real system. We observe that for any energy-proportional system as reference system, i.e. for any slope m which is the EI of the energy-proportional system, both EE metrics are identical.

$$\eta(x) = \frac{h(x)}{f(x)} = \frac{mx}{f(x)} = \nu(x) \tag{32}$$

This is an important relationship in practice. For example, a value of $\eta(x) = \nu(x) = 0.5$ means that the ideal system requires only half of the EC of the real system. It also means that the real system only processes half of the traffic volume of the ideal system. An energy-proportional ideal system is therefore a recommended reference system in practice.

The bit-per-joule efficiency $\gamma(x)$ of the real system is the inverse of the energy intensity. We obtain the following

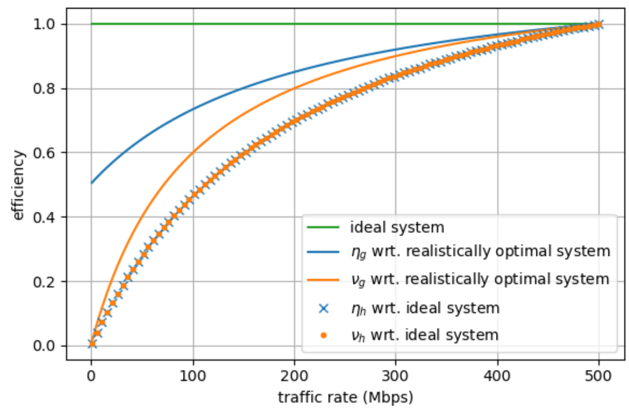

FIGURE 7. Energy consumption-related (η) and output-related energy efficiency (ν) of the real system in comparison with the energy-proportional ideal system (i.e. η_h, ν_h) and the realistically optimal system (i.e. η_g, ν_g).

relationships with the EE metrics $\eta(x) = \nu(x)$ when using energy-proportional systems as reference. The EI of the ideal system corresponds to the constant m.

$$\gamma(x) = \frac{x}{f(x)} = \frac{\eta(x)}{m} = \frac{\nu(x)}{m} \tag{33}$$

Thus, the bit-per-joule efficiency γ is a non-normalized efficiency measure. To obtain normalized values in [0; 1], γ can be multiplied by m, yielding the efficiency in comparison to the energy-proportional system with EI m.

Theorem 2 (Energy-Proportional Reference System): Consider a real system that is characterized by the system function $f(x)$. Using an energy-proportional system as reference with system function $h(x) = mx$ and constant $m > 0$, the relationship between the energy efficiency measures is as follows.

$$\eta(x) = \nu(x) = m \cdot \gamma(x) \tag{34}$$

RELATIONSHIP TO ENERGY PROPORTIONALITY INDEX (EPI)

The Energy Proportionality Index (EPI) represents the difference between ideal and measured power consumed by the equipment [36]. In Figure 8, the power (in Watt) consumed by a device is plotted against the load on the device (in Gbps). Ideally, the power consumed should be proportional to the load, with the maximum power M consumed being as low as possible. The real behaviour of network devices follow the dashed line marked, with the device's power consumption I even under idle (no load) conditions. Then, EPI is defined as follows [36].

$$\text{EPI} = \frac{M - I}{M} \tag{35}$$

Thereby, EPI approximates the real system by a linear model

$$f(x) = \alpha x + \beta, \ 0 \le x \le x_{\max} \tag{36}$$

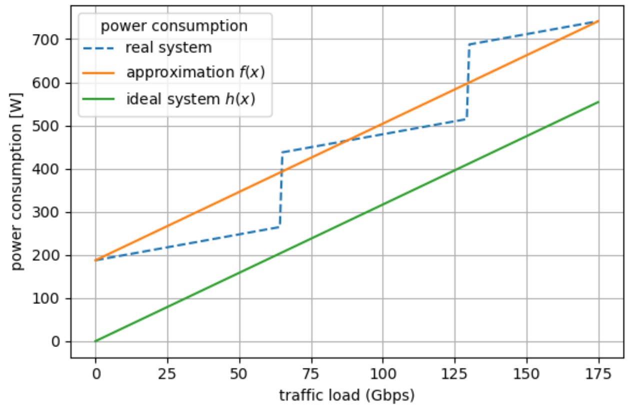

FIGURE 8. Visualization of the interpretation of the energy proportionality index (EPI) regarding the consumption- and output-related energy efficiency with ideal system $h(x)$. The real system function is approximated by a linear model $f(x) = \alpha x + \beta$ for EPI and $h(x) = \alpha x$.

with $f(0) = I$ and $f(x_{\max}) = M$, see Figure 8.

$$\text{EPI} = \frac{f(x_{\max}) - f(0)}{f(x_{\max})} = \frac{\alpha x_{\max}}{\alpha x_{\max} + \beta} \tag{37}$$

Now, we consider an energy-proportional system with

$$h(x) = \alpha x \tag{38}$$

Due to the energy-proportional ideal system, it is

$$\eta(x_{\max}) = \nu(x_{\max}) = \frac{\alpha x_{\max}}{\alpha x_{\max} + \beta} = \text{EPI}. \tag{39}$$

Thus, EPI quantifies the energy efficiency at the maximum load $x_{\max}$ in relation to an energy-proportional ideal system $h(x) = \alpha x$ with slope α where the real system is approximated by a linear model $f(x) = \alpha x + \beta$, see Figure 8. Therefore, EPI is a special case of our generic EE measures.

C. RELATIONSHIPS FOR IDEAL LINEAR SYSTEMS WITH OFFSET

Instead of an energy-proportional system, a linear model $h(x)$ with offset $c > 0$ is considered as reference system for evaluating the energy efficiency of the real system with system function $f(x)$.

$$h(x) = mx + c \tag{40}$$

Then, we derive the following energy efficiency measures and observe the following relationship.

$$\eta(x) = \frac{mx + c}{f(x)} \quad \geq \quad \nu(x) = \frac{mx}{f(x) - c} \tag{41}$$

This relationship can be easily shown. Since for the ideal system with system function $h(x)$, it is $h(x) \leq f(x)$ and the relationship $\eta(x) \geq \nu(x)$ follows.

$$\frac{mx + c}{f(x)} \geq \frac{mx}{f(x) - c} \implies (mx + c)(f(x) - c) \geq mxf(x)$$
$$\implies cf(x) - cmx - c^2 \geq 0 \implies f(x) \geq mx + c = h(x)$$

In other words, for ideal linear systems with any offset $c > 0$, the EC-related energy efficiency $\eta(x)$ is always larger than the output-related energy efficiency $\nu(x)$. Equality holds for $c = 0$, i.e., an energy-proportional system, see Section IV-B.

The normalized bit-per-joule efficiency $m\gamma(x) = \frac{mx}{f(x)}$ is then always less than both EE measures.

Theorem 3 (Linear Reference System): Consider a real system that is characterized by the system function $f(x)$. Using a linear ideal system as reference with system function $h(x) = mx + c$ and constants $m > 0$ and $c \geq 0$, the relationship between the energy efficiency measures is as follows.

$$\eta(x) \geq \nu(x) \geq m \cdot \gamma(x) \tag{42}$$

D. RELATIONSHIPS FOR SYSTEMS WITH IDLE OFFSET

An ideal reference system with a constant offset $c > 0$ is now considered. The ideal system function $h(x)$ can be written in the following form

$$h(x) = h_1(x) + c \ \text{ with } h(0) = c, \ h_1(0) = 0 \tag{43}$$

using the shifted system function $h_1(x) = h(x) - c$, such that the ideal system consumes energy $h(0) = c$ in idle mode; or equivalently $h_1(0) = 0$. The inverse system function is

$$h^{-1}(y) = h_1^{-1}(y - c) \,. \tag{44}$$

Accordingly, the shifted system function $f_1(x) = f(x) - c$ of the real system yields

$$f(x) = f_1(x) + c \ \text{ with } f(x) \geq h(x) \,. \tag{45}$$

Then, the EE measures are derived as follows.

$$\eta(x) = \frac{h(x)}{f(x)} = \frac{h_1(x) + c}{f_1(x) + c} \tag{46}$$

$$\nu(x) = \frac{x}{h^{-1}(f(x))} = \frac{x}{h_1^{-1}(f_1(x))} \tag{47}$$

First, we observe that the output-related EE ν is independent of the constant c of energy consumption in idle mode. In fact, ν quantifies how much work the ideal system could process with the energy consumption of the real system. In Figure 4, the constant c is, however, just shifting both curves f_1 and h_1, and therefore the relationship x/x^* is independent of c. In contrast, the EC-related EE $\eta(x)$ depends on the offset c.

Second, for large offsets c, dominating the energy consumption for processing the traffic, η is approaching 1. Formally, $\lim_{c\to\infty} \eta(x) = 1$. However, ν is independent of c. This observation can be interpreted as follows. Considering the energy consumption, the real system and the ideal system are dominated by the constant offset and both systems have a similar EC. Therefore, the energy efficiency η is close to optimum ($\eta = 1$). In contrast, the output-related EE considers how much work could be additionally processed, see Eq.(44).

Third, the system is considered in idle mode, $x = 0$. With $h_1(0) = 0$, it is $\eta(0) = \frac{c}{f_1(0)+c} \geq 0$. However, $\nu(0) = 0$, which means that the most inefficient way for operating the system is in idle mode due to the idle offset, while no output

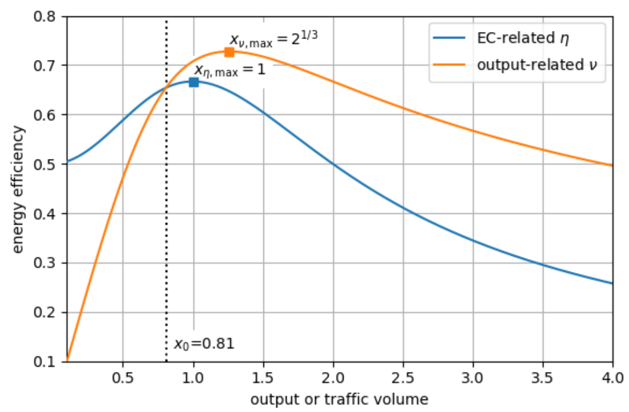

FIGURE 9. **Super-linear ideal system with $h(x) = x^2 + 1$ and real system with $f(x) = x^3 + 2$ lead to the energy efficiency measures η and ν. The relationship $\nu < \eta$ changes at the point x_0. The optimal operational points leading to the corresponding maximum EE measure are also different.**

is generated. On the other hand, $\eta(0) \geq 0$ indicates if the real and ideal system need to be available and operating, even without generating any output, e.g. a base station listening for incoming traffic from mobile phones. Then, the EC-related EE quantifies that ratio of energy consumption of the ideal and real system.

Theorem 4 (Reference System With Idle Offset): Consider a real system that is characterized by the system function $f(x) \geq h(x)$. Using an ideal system as reference with system function $h(x) \geq c$ with constant offset $c \geq 0$ and $h(0) = c$, the output-related EE $\nu(x)$ is independent of c, in contrast to the consumption related EE $\eta(x)$.

E. INEQUALITIES BETWEEN CONSUMPTION- AND OUTPUT-RELATED EE

For energy-proportional systems, the two measures are identical. However, the question remains, what is the relationship if the reference system is different. To this end, we consider exemplary a super-linear ideal system with characteristic function

$$h(x) = x^2 + 1\ , \tag{48}$$

while the real system's energy consumption is

$$f(x) = x^3 + 2 \geq h(x)\ . \tag{49}$$

Then, we obtain the following EE measures.

$$\eta(x) = \frac{h(x)}{f(x)} = \frac{x^2+1}{x^3+2} \tag{50}$$

$$\nu(x) = \frac{x}{h^{-1}(f(x))} = \frac{x}{\sqrt{x^3+1}} \tag{51}$$

Figure 9 shows the energy efficiency for the real system for both metrics. This example demonstrates that no general relationship between ν and η exists for arbitrary system functions of the real and the ideal system – in contrast to linear reference models with $\eta \geq \nu$, as shown in Section IV-C. Numerically, we find that $\eta(x) \leq \nu(x)$ for $x \leq x_0 = 0.808731$ with x_0 as root of $x^5 + x^2 - 1 = 0$. Otherwise, $\nu(x) < \eta(x)$ for $x > x_0$.

Another interesting observation is that the optimal operational points are different in that example, depending on whether the output- or consumption-related EE is used. The maximum EE $\eta_{\max}$ is reached for $x_{\eta,\max} = 1$, while $\nu_{\max}$ is reached for $x_{\nu,\max} = 2^{1/3} \approx 1.26$.

V. PRACTICAL APPLICATIONS AND INSIGHTS

The theoretical insights show that an energy-proportional system with corresponding slope m is recommended as the ideal reference system. The slope m is the energy intensity of the ideal system. In that case, the different EE measures $\nu(x) = \eta(x)$ are identical and $\nu(x) = \eta(x) = m\gamma(x)$. If expert knowledge is available to identify the minimum required energy consumption in idle mode, the corresponding linear model with offset is recommended. In that case, $\eta(x) \geq \nu(x)$.

In the following, important insights and practical applications of the EE metrics are provided. First, the benchmarking of two systems is considered (Section V-A). An illustrative example is used to demonstrate decision-making on networking equipment by considering EE as well as monetary costs. Then, we consider the value of a system in terms of Quality of Experience (QoE) instead of the amount of processed traffic (Section V-B). Finally, limitations and the usage of energy intensity are considered in particular (Section V-C).

A. BENCHMARKING OF SYSTEMS

Two real systems are now compared regarding their energy efficiency. The energy consumption curves are $f_1(x)$ and $f_2(x)$, respectively.

1) BENCHMARKING FOR SAME TRAFFIC VOLUME

For the consumption-related EE, the measures $\eta_1(x)$ and $\eta_2(x)$ are computed and the ratio is compared. In practice, we may observe a single measurement point $x = \theta$ for both systems. Then, the energy efficiency η of system 1 is better than for system 2 if

$$\eta_1(\theta) > \eta_2(\theta) \implies \frac{\eta_1(\theta)}{\eta_2(\theta)} = \frac{h(\theta)}{f_1(\theta)} \Big/ \frac{h(\theta)}{f_2(\theta)} = \frac{f_2(\theta)}{f_1(\theta)} > 1$$
$$\implies f_2(\theta) > f_1(\theta)\ . \tag{52}$$

This means that the energy consumption $f_2(\theta)$ of system 2 is larger than the consumption $f_1(\theta)$ of system 1 when the same traffic volume θ is processed. For that comparison, no reference system and its energy consumption $h(\theta)$ is required.

Considering the bit-per-joule efficiency γ_1 and γ_2, it is

$$\gamma_1(\theta) > \gamma_2(\theta) \implies \frac{\gamma_1(\theta)}{\gamma_2(\theta)} = \frac{\theta}{f_2(\theta)} \Big/ \frac{\theta}{f_1(\theta)} = \frac{f_2(\theta)}{f_1(\theta)} > 1$$
$$\implies f_2(\theta) > f_1(\theta)\ . \tag{53}$$

Hence, both measures can be utilized to benchmark the energy efficiency of two systems. The ratio of the measures indicates the ratio of the corresponding energy consumptions.

Note that no reference system $h(\theta)$ needs to be specified or measured.

Similarly, the energy intensity I_1 and I_2 can also be used. If the energy intensity of system 1 is smaller than of system 2, the system 1 is more energy efficient.

$$I_1(\theta) < I_2(\theta) \implies \frac{I_1(\theta)}{I_2(\theta)} = \frac{f_1(\theta)}{\theta} / \frac{f_2(\theta)}{\theta} = \frac{f_1(\theta)}{f_2(\theta)} < 1 \implies f_2(\theta) > f_1(\theta) . \tag{54}$$

The situation is different when considering the output-related energy efficiency ν. To this end, the inverse function h^{-1} is required. Since $h(x)$ is strictly monotonically increasing, its inverse function is also strictly monotonically increasing.

$$\nu_1(\theta) > \nu_2(\theta) \implies \frac{\theta}{h^{-1}(f_1(\theta))} > \frac{\theta}{h^{-1}(f_2(\theta))} \tag{55}$$

$$\implies h^{-1}(f_2(\theta)) > h^{-1}(f_1(\theta)) \implies f_2(\theta) > f_1(\theta) \tag{56}$$

Note the ratio of the output-related EE measures is the ratio of the energy consumptions without the constant offset c. But note that $\frac{f_2(\theta)}{f_1(\theta)} \neq \frac{\nu_1(\theta)}{\nu_2(\theta)}$ in general.

Theorem 5 (Benchmarking for Same Traffic Volume): Consider two systems for which their energy consumption $f_1(\theta)$ and $f_2(\theta)$ is obtained for the traffic volume θ. If $f_2(\theta) > f_1(\theta)$, then it holds

$$\frac{\eta_1(\theta)}{\eta_2(\theta)} = \frac{\gamma_1(\theta)}{\gamma_2(\theta)} = \frac{I_2(\theta)}{I_1(\theta)} = \frac{f_2(\theta)}{f_1(\theta)} > 1 , \quad \frac{f_2(\theta)}{f_1(\theta)} \neq \frac{\nu_1(\theta)}{\nu_2(\theta)} > 1 \tag{57}$$

for any ideal reference system $h(x)$.

2) BENCHMARKING FOR SAME ENERGY CONSUMPTION

Alternatively, the same amount of energy e may be considered and how much traffic x_1 and x_2 can be processed by system 1 and system 2, respectively. Then, the EE measures are as follows.

$$\gamma_1(x_1) = \frac{x_1}{e} > \gamma_2(x_2) = \frac{x_2}{e} \implies x_1 > x_2 \tag{58}$$

$$I_1(x_1) = \frac{e}{x_1} < I_2(x_2) = \frac{e}{x_2} \implies x_1 > x_2 \tag{59}$$

The output-related EE is as follows.

$$\nu_1(x_1) = \frac{x_1}{h^{-1}(e)} > \nu_2(x_2) = \frac{x_2}{h^{-1}(e)} \implies x_1 > x_2 \tag{60}$$

Hence, the measures indicate that system 1 can process more traffic than system 2 with the same amount of energy.

The consumption-related EE requires the energy consumption of the ideal system to compare the processed traffic volume. For an ideal system, the energy consumption $h(x)$ is strictly monotonically increasing, i.e., $x_1 > x_2 \implies h(x_1) > h(x_2)$.

$$\eta_1(x_1) = \frac{h(x_1)}{e} > \eta_2(x_2) = \frac{h(x_2)}{e} \tag{61}$$

$$\implies h(x_1) > h(x_2) \implies x_1 > x_2 \tag{62}$$

Note that $\frac{x_1}{x_2} \neq \frac{\eta_1(x_1)}{\eta_2(x_2)}$ in general.

Theorem 6: (Benchmarking Under Same Energy Consumption): Consider two systems with the same energy consumption e, which are able to process a traffic volume x_1 and x_2, respectively. If $x_1 > x_2$, then it holds

$$\frac{\nu_1(x_1)}{\nu_2(x_2)} = \frac{\gamma_1(x_1)}{\gamma_2(x_2)} = \frac{I_2(x_2)}{I_1(x_1)} = \frac{x_1}{x_2} > 1 , \quad \frac{x_1}{x_2} \neq \frac{\eta_1(x_1)}{\eta_2(x_2)} > 1 \tag{63}$$

for any ideal reference system $h(x)$.

3) BENCHMARKING AT ARBITRARY POINTS

Now, we compare two systems by arbitrary measurement points. System 1 processes the traffic volume x_1 and requires energy $f_1(x_1) = e_1$, while system 2 processes x_2 with an EC of $f_2(x_2) = e_2$. However, we cannot derive any general relationships from those measures.

$$\eta_1(x_1) = \frac{h(x_1)}{e_1} \qquad \eta_2(x_2) = \frac{h(x_2)}{e_2} \tag{64}$$

$$\nu_1(x_1) = \frac{x_1}{h^{-1}(e_1)} \qquad \nu_2(x_2) = \frac{x_2}{h^{-1}(e_2)} \tag{65}$$

$$\gamma_1(x_1) = \frac{x_1}{e_1} \qquad \eta_2(x_2) = \frac{x_2}{e_2} \tag{66}$$

Therefore, we consider a concrete example, which is illustrated in Figure 10. The measurement points as well as the energy efficiency values are provided in Table 2. Intuitively, we argue that system 2 is more energy efficient than system 1, since the energy consumption is similar (for low traffic volumes) or smaller (for larger traffic volumes) than for system 1.

However, *the two systems under operation are compared*, which includes the actual traffic processed by each system and the resulting energy consumption. The bit-per-joule efficiency γ indicates that system 1 is better than system 2 by a factor of 1.9, see the column ratio in Table 2. In contrast, the consumption-related EE η are almost identical for both systems. Furthermore, the output-related EE ν shows that system 2 is more energy-efficient than system 1.

In our example, system 2 is designed to cope with larger amounts of traffic more efficiently than system 1 (with respect to energy consumption). This explains that the output-related efficiency is better and system 2 is operated at a larger traffic volume. System 1 is designed to cope with smaller traffic volume and therefore requires less energy consumption in that case. Hence, for arbitrary measurement points, no general relationship between the EE measures is found.

Limit 1 (Comparing Systems at Arbitrary Measurement Points): If systems are compared at arbitrary measurements points, i.e. different energy consumptions for the traffic volumes processed in system 1 and system 2, the conclusion which system is better wrt. energy efficiency may be different for the measures η, ν, γ.

The comparison at arbitrary points is valid, but its correct interpretation must be emphasized. The results may show

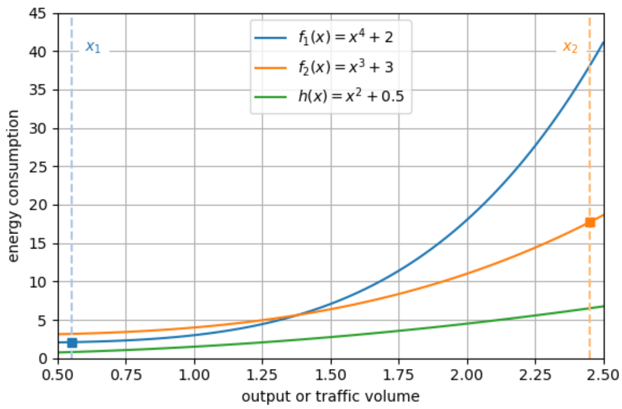

FIGURE 10. Example for comparing two systems at arbitrary measurements points x_1 and x_2, marked with squares.

that system 1 is better wrt. to a particular EE metric than system 2 at the measurement points. More precise, the actual operation of system 1 and the processed traffic volume x_1 is better wrt. to a particular EE metric than the actual operation of system 2 and its processed traffic volume x_2. However, it cannot be concluded that system 1 is better at other measurement points. For example, in Figure 10, if the actual traffic volume in system 1 increases, e.g. $x_1 = 1.75$ beyond the intersection point of f_1 and f_2, then the energy consumption of system 2 is lower and the consumption-related EE ν_2 of system 2 will be larger, i.e. $\nu_2 > \nu_1$. This is especially important to understand, since energy intensities are often reported on an annual basis and systems are compared based on the EI values. However, in future years, the traffic volumes for the system under comparison may change, and therefore the conclusion which system is better cannot be derived.

The same observation is also true, if the systems are compared for the same traffic volume $\theta = x_1 = x_2$. Depending on θ, either system 1 or system 2 is better wrt. to the energy efficiency measures, cf. Figure 10.

Limit 2 (Comparing Systems in General): The comparison of systems at the same or arbitrary measurements points does not allow conclusions for other measurements, e.g., for future operation of the systems.

4) DECISION ON EQUIPMENT WRT. ENERGY EFFICIENCY AND COSTS

A high degree of energy efficiency is a desired property of systems and devices, and typically newer devices are operating more energy efficient than older ones. However, when it comes to the decision whether an existing device should be replaced by a new, more energy efficient one, the investment costs need to be considered. The discussions on device replacement are also currently held in an IETF draft on the usage of inventory-maintained information for assessing the adaptation of existing devices to eco-design [50]. To this end, the consumption-related energy efficiency is a helpful measure.

Let us consider that system 0 and system 1 have the consumption-related EE $\eta_1(x)$ and $\eta_2(x)$, respectively. Then, Theorem 5 states that the relation between the measures is identical to the inverse ratio of the energy consumption.

$$\frac{\eta_1(x)}{\eta_0(x)} = \frac{f_0(x)}{f_1(x)} = k \implies f_0(x) = kf_1(x) \tag{67}$$

The investment for buying the new system 1 is B (in €). The operational costs for running the system in terms of energy consumption is Ω (in €/J). During the remaining lifetime, the currently deployed system 0 may process an overall traffic volume x. Then, the costs for the energy consumption are Y_0, while for the new system 1 the investment B has to be added to obtain the overall costs Y_1.

$$Y_0 = \Omega \cdot f_0(x) \tag{68}$$
$$Y_1 = \Omega \cdot f_1(x) + B \tag{69}$$

If the overall costs Y_1 are less than the costs Y_0, the currently running system 0 should be replaced by system 1. This gives us the following relation.

$$Y_1 < Y_0 \implies \Omega f_1(x) + B < \Omega f_0(x) = \Omega k f_1(x) \tag{70}$$
$$\implies k > \frac{B + \Omega f_1(x)}{\Omega f_1(x)} = \frac{Y_1}{Y_1 - B} \tag{71}$$

In other words, if the energy efficiency of system 1 is k-times higher than the energy efficiency of the existing system 0, it is recommended to replace the existing one with the new system 1. Thereby, the threshold k is the ratio of the sum of the Capital Expenditure (CAPEX) and the Operating Expenses (OPEX), which is Y_1, divided by the OPEX ($Y_1 - B = \Omega f_1(x)$).

B. CONSIDERING THE VALUE OF THE OUTPUT OF A SYSTEM

In the previous discussions, the energy efficiency metrics consider as output the traffic volume processed by a system. However, instead of the traffic, the output may also consider the value or utility of the traffic volume being processed.

1) EXAMPLE: VIDEO STREAMING AND QOE

To this end, an example of video streaming is considered to quantify its energy efficiency. To be more precise, the use case considers the energy consumption of video streaming at the end user's device, which is the system under test here. The video bitrate resulting from an appropriate encoding scheme as well as the requested video bitrate by the end user's video player is a key factor of the Quality of Experience (QoE) as experienced by the user. We use the QoE model suggested in [51], which allows a mapping between the video bitrate and the Mean Opinion Score (MOS). The MOS quantifies the QoE on a 5-point scale, with 1 indicating poor quality and 5 indicating excellent quality. At the same time, measurements of the power consumption of video streaming reveal a linear power consumption model [52]. Please note that only the energy consumption of the end device, but not from the data centre or the communication network, are considered in this example. We used realistic values for the coefficients of the linear model which fit to a desktop PC [52].

Figure 11 provides the power consumption $f(x)$ and $h(x)$ of the real system and the ideal energy-proportional system depending on the video bitrate, respectively. The slope m is derived according to Eq.(8). On the right y-axis, the MOS values are additionally provided (dashed curve) showing the logarithmic relationship between the MOS values $q(x)$ and the video bitrate x.

$$f(x) = \alpha x + \beta \tag{72}$$
$$h(x) = mx \tag{73}$$
$$q(x) = k \log x + d \tag{74}$$

Figure 12 considers now the MOS as output of the system instead of the actual traffic. To this end, the power consumption curves are transformed to map the achieved MOS $\mu = q(x)$ to the corresponding power consumption $f_q(\mu)$ of the real system and $h_q(\mu)$ of the ideal system. To this end, the inverse function $q^{-1}(\mu)$ is utilized to map a MOS score to the corresponding video bitrate x. Accordingly, we obtain the following transformed functions.

$$q^{-1}(\mu) = e^{\frac{\mu-d}{k}} \tag{75}$$
$$f_q(\mu) = \alpha q^{-1}(\mu) + \beta = \alpha \cdot e^{\frac{\mu-d}{k}} + \beta \tag{76}$$
$$h_q(\mu) = m q^{-1}(\mu) = m \cdot e^{\frac{\mu-d}{k}} \tag{77}$$

However, we observe that the ideal system, which is energy-proportional concerning the amount of traffic, is not a linear function in the transformed domain. Therefore, we provide a linear model $h^*(\mu) = m^* x + c^*$ of an ideal system with respect to the MOS value μ. We use expert knowledge to derive the coefficients m^* and c^*. In fact, the minimal MOS (1.0) should lead to the minimal power consumption. The slope is obtained by considering the minimum energy intensity $I_q(\mu) = f_q(\mu)/\mu$, which is provided in W/MOS.

The linear ideal system regarding the QoE of the system as output of the system is therefore as follows.

$$h^*(\mu) = m^* \cdot \mu + c^* \tag{78}$$

Now, we compute the energy efficiency measures $\eta(x)$, $\nu(x)$ with respect to the traffic x. Since the reference system $h(x)$ is energy-proportional, both measures are identical. However, we can also compute the EE measures $\eta_q(\mu)$, $\nu_q(\mu)$ in the transformed QoE domain.

$$\eta(x) = \nu(x) = \frac{h(x)}{f(x)} = \frac{mx}{\alpha x + \beta} \tag{79}$$
$$\eta_q(\mu) = \frac{h_q(\mu)}{f_q(\mu)} = \frac{m^* \mu + c^*}{\alpha \cdot e^{\frac{\mu-d}{k}} + \beta} \tag{80}$$
$$\nu_q(\mu) = \frac{\mu}{h^{*-1}(f_q(\mu))} = \frac{m^* \mu}{\alpha \cdot e^{\frac{\mu-d}{k}} + \beta - c^*} \tag{81}$$

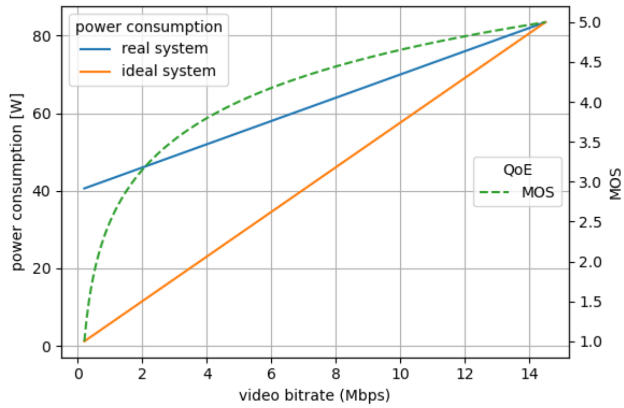

FIGURE 11. Power consumption and MOS values for video streaming depending on the video bitrate. An energy-proportional ideal system $h(x) = mx$ is considered as reference system.

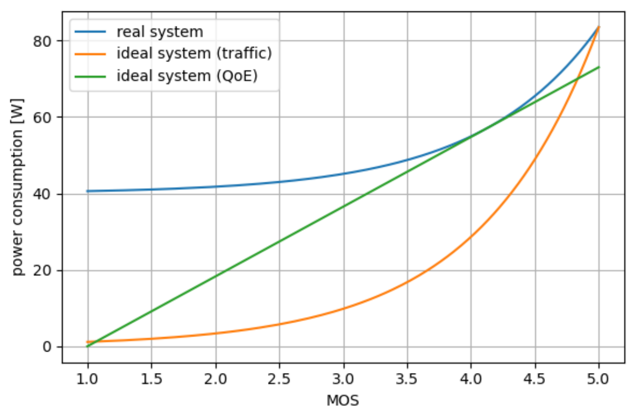

FIGURE 12. Transformation to MOS values as output of the system instead of video traffic bitrates. A linear ideal system $h^*(\mu)$ is provided which maps the output in terms of MOS μ to power consumption. Additionally, the transformed ideal system function $h_q(\mu)$ and the transformed real system function $f_q(\mu)$ are depicted.

Figure 13 visualizes the energy efficiency measures. For comparing the measures, they are all plotted depending on the MOS. Thus, for the EE measures related to the traffic, we plot $\eta_x(\mu) = \eta(q^{-1}(\mu))$. We observe that the resulting EE curves are very different. In particular, just considering the traffic (i.e. video bitrate), yields an optimal energy efficiency if the full video bitrate of 14.5 Mbps is used, yielding MOS 5. In contrast, the energy efficiency measures which use the MOS as output of the system are maximal for 5.66 Mbps resulting in a MOS value of 4.12.

This example demonstrates that it is important to focus on the right output of the system in the energy efficiency analysis. We clearly want to emphasize that the identification of optimal operational points is however a multi-objective optimization problem in practice. Energy consumption and energy efficiency are only one important dimension. However, the performance, the QoS, the QoE, as well as other factors like resilience need to be considered as well. The same is also true when two systems are compared. Energy

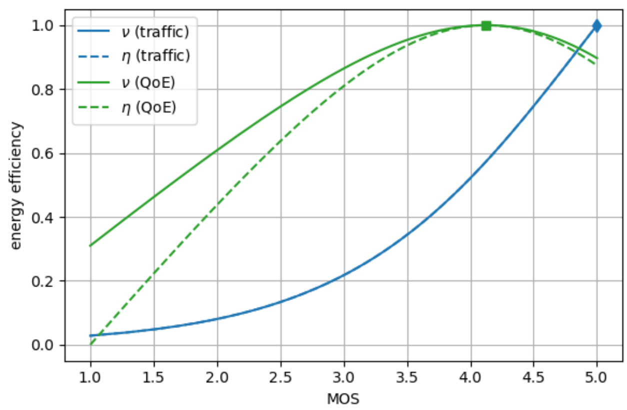

FIGURE 13. Energy efficiency measures $\nu(x) = \eta(x)$ which are computed based on the traffic as output (Figure 11) as well as EE measures $\nu_Q(\mu)$, $\eta_Q(\mu)$ based on the MOS as output of the system (Figure 12). For comparing the EE measures, they are plotted depending on MOS.

efficiency is one dimension, but there are more aspects to consider. For example, a system 1 which is more resilient than another system 2 may have a worse energy efficiency, e.g. by using backup devices which take over in case of errors. In this article, we therefore present precisely those measures that are suitable for energy efficiency and how they can be used in practice.

TABLE 2. Energy efficiency for the example in Figure 10.

Measure M_i	System 1	System 2	Ratio $\frac{M_1}{M_2}$	Better
x_i	0.55	2.45	0.22	System 2
$f_i(x)$	2.09	17.71	0.12	System 1
η_i	0.38	0.37	1.04	System 1
ν_i	0.44	0.59	0.74	System 2
γ_i	0.26	0.14	1.90	System 1

TABLE 3. Example of multi-objectives related to sustainability.

Measure	System A	System B	System C
energy cons. per year	10 GW h	10 GW h	100 GW h
data volume per year	1 Mbit	10 Tbit	1000 Tbit
energy intensity	10 000 W h/bit	0.001 W h/bit	0.0001 W h/bit
utilization	0.000 01 %	5 %	100 %
value	1 Byte saves 1 life	20 000 students with 30 h of lectures/week	3 million users paying 30 € per month
description	emergency warning system (earthquakes, floods, ...)	video conferencing system for education (HD)	live streaming system for public sport events (4K)

2) ILLUSTRATIVE EXAMPLE: VALUES AND KVIS BEYOND ENERGY EFFICIENCY

A more illustrative example is sketched in Table 3. It is tempting to use the energy efficiency or energy intensity for the evaluation of systems. However, let us consider three exemplary systems A, B, C in the following to illustrate the need to consider the value instead of traffic. In particular, energy intensity may be one single Key Value Indicator (KVI), as discussed in [53]. The three systems are described in the Table 3. The key question is: *Which system is better regarding sustainability?* Clearly, System A and B have a lower total energy consumption than System C. Nevertheless, the energy intensity is much better for System C. Is System C therefore more energy-efficient than System A and B? Yes, but only at its current operation and measurement points (see Limit 1). We may also need to consider the utilization of the systems. System B is only utilized with 5%. We assume that increasing the utilization by factor 20, i.e. up to 100%, would not affect the total energy consumption per year, but allows processing 200 TB. Hence, System B would have an energy intensity 0.05 mWh/B at 100% utilization and it would be more energy-efficient than System C. This limitation of prediction capabilities is discussed in Section V-C. Is therefore System B better than System C? Finally, we have a closer look at the purpose and the output of the three systems. System A is an emergency warning system for floods and earthquakes. Each warning message may save a life in an emergency. In contrast, System B is a video conferencing system for education purposes and serves up to 20 000 students with 30 h of lectures in HD video quality per week. Finally, System C is providing live streams of public (live) sport events in 4K video resolution. There are 3 million customers paying 30 € per month for using System C. This example demands for the consideration of values and measurement of KVIs to quantify the value of the systems. Clearly, the KVIs are use-case dependent and the use-cases define the concrete values to be considered. The example and the three different systems touch the different pillars of sustainability: human (A), social (A,B), economic (C) and environmental (A, B, C).

[53] proposes a structured KVI framework tailored to the ICT research and development (R&D) sector by leveraging established definitions, frameworks, and value identification methods. The KVI framework comprises five steps, starting from the use case-related identification of values to the assessment of value outcomes. The KVI framework is aimed to be a useful tool for the ICT research sector to identify and estimate value outcomes from technology use. Energy efficiency is thereby one important aspect of the environmental sustainability.

C. LIMITS AND USAGE OF ENERGY INTENSITY

Due to its widespread usage of energy intensity in practice, some crucial observations and limits of EI are summarized. For the illustration of numerical results, the linear energy consumption model of a 5G base station [49] is used, as discussed in Section IV-A.

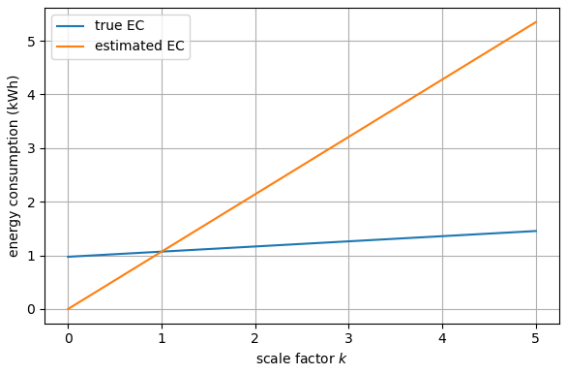

FIGURE 14. The estimated EC $\widetilde{f}(kx)$ and the true EC $f(kx)$ for the linear 5G base station model [49] over one hour, depending on the traffic scale factor k. Note that there is a positive offset in the linear EC model $c > 0$.

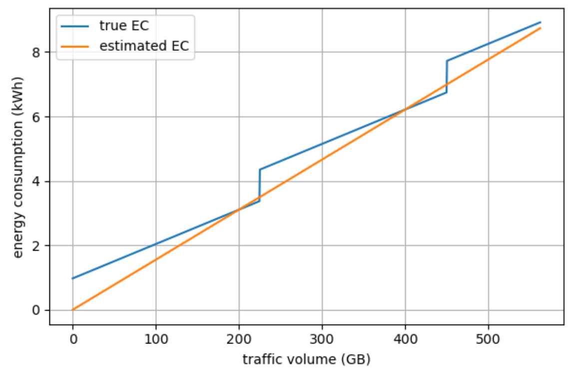

FIGURE 15. The prediction of the EC based on EI ignores the system behaviour. Here, the maximum capacity is 225 GB, then, an additional device is switched on. The EI is given for $x_0 = 200$ GB.

1) INCREASED TRAFFIC ASSUMES SCALING DEVICES

With the EI $I(x_0)$ given for a traffic volume x_0, it is tempting to predict the energy consumption by multiplying the EI with an arbitrary traffic volume x. The estimation $\widetilde{f}(x)$ of the energy consumption for traffic volume x is then

$$\widetilde{f}(x) = I(x_0) \cdot x = \frac{f(x_0)}{x_0} \cdot x \neq f(x) , \qquad (82)$$

which is not identical to the true EC $f(x)$ in general. Only in the case of an energy-proportional system with $f(x) = mx$, it is $I(x) = m$ and $\widetilde{f}(x) = f(x)$.

Consider now a linear EC model, such that the true energy consumption and the energy intensity are as follows.

$$f(x) = mx + c \qquad I(x) = \frac{mx + c}{x} = m + \frac{c}{x} \qquad (83)$$

The estimated EC uses $I(x_0)$ and with $x = k \cdot x_0$ follows

$$\widetilde{f}(x) = \frac{mx_0 + c}{x_0} \cdot kx_0 = k(mx_0 + c) = kf(x_0) . \qquad (84)$$

However, the true energy consumption is

$$f(x) = f(kx_0) = mkx_0 + c \neq \widetilde{f}(kx_0) = \widetilde{f}(x) . \qquad (85)$$

This means that the estimated energy consumption in Eq.(84) is wrong and does not match the true energy consumption in Eq.(85). The estimated EC simply scales the number of devices with a single device having $f(x_0)$ of energy consumption, resulting in a total EC of $kf(x_0)$. Only for energy-proportional systems or devices, the estimation is correct. Note that "devices" may be also parts, e.g. of a base station like baseband units (BBUs). Figure 14 illustrates the true and the estimated EC for the linear EC model of a 5G base station [49]. Only for $k = 1$, the estimation is correct, since the energy intensity is aligned with the corresponding volume. Otherwise, strong discrepancies are observed. In practice, it is of utmost importance to recognize that limit when using EIs for EC predictions.

Limit 3 (Scaling Devices): Predicting the EC using the EI for traffic increased by factor k assumes scaling the number of devices by factor k – which is wrong in general.

2) PREDICTION BASED ONLY ON EI IGNORES SYSTEM BEHAVIOUR

Another crucial point is that the prediction of the energy consumption based on EI may ignore the true system behaviour. For example, we consider that the base station can only handle a maximum traffic volume $x_{\max}$ during the considered time frame. If the traffic is exceeded, an additional base station (BS) or an additional sector of the existing BS is switched on. In total, there are $n = \lceil \frac{x}{x_{\max}} \rceil$ BSs switched on. The energy consumption for a single base station is $f_0(x) = mx + c$. Then, the overall energy consumption is a linear function with steps at multiples of $x_{\max}$ for adding another BS, see Figure 15.

$$f(x) = mx + \left\lceil \frac{x}{x_{\max}} \right\rceil c \qquad (86)$$

In contrast, the estimated EC is a linear function for any given EI $I(x_0)$, see Figure 15. For example, consider the case that $x_0 < x_{\max}$ and $n = 1$. Then, $I(x_0) = mx_0 + c$.

$$\widetilde{f}(x) = I(x_0) \cdot x = \frac{mx_0 + c}{x_0} \cdot x \qquad (87)$$

Limit 4 (Ignored Effects): Predictions based on EI may ignore relevant effects and system behaviour. For example, capacity limits require additional devices.

However, we also observe that for large n, the overall energy consumption can be well approximated as energy-proportional system. Note that the energy consumption is then a function of the number n of devices, $\widetilde{f}(n) = n \cdot f_0(x_{max})$. The relative error is then in reasonable bounds.

3) ENERGY INTENSITY IMPROVEMENTS BY INCREASED TRAFFIC

The linear EC model of the 5G base station [54] is assumed. The true EI $I(x)$ is provided in Eq.(83). With increasing traffic volume, the EI declines. One gets the impression that the systems improves its energy consumption. However, in fact, the system is just better utilized and runs more efficiently. Figure 16 shows how the EC increases, while the EI decreases.

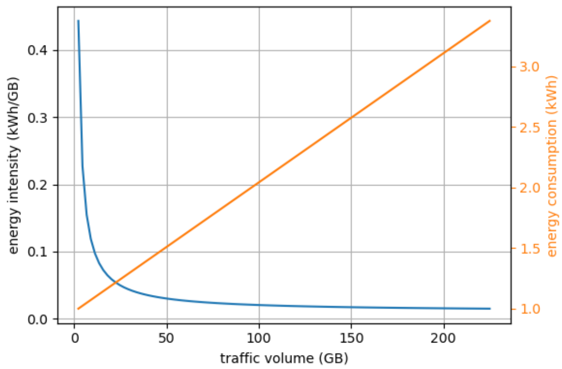

FIGURE 16. The EI improves with increasing traffic volume. In contrast, the estimated EI assumes the constant value $I(x_0)$, for which the EI is provided.

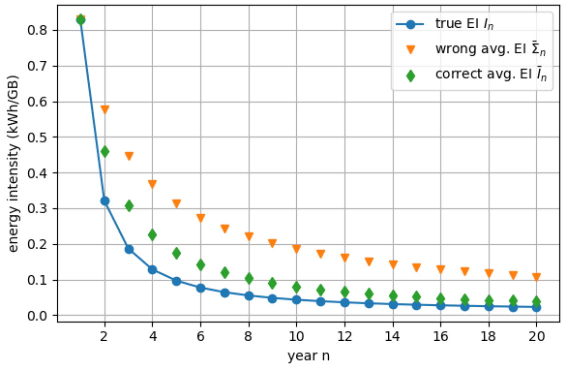

FIGURE 17. The average $\bar{\Sigma}_n$ of the intensities is calculated for year 1 up to year n (x-axis). The $\bar{\Sigma}_n$ is compared to the correct EI $\bar{I}_n$ over the entire time from year 1 to year n. The true EI I_n per year n is additionally provided.

Limit 5 (EI Improvements): Energy intensity improvements do not mean reduced energy consumption.

4) AVERAGES OF ENERGY INTENSITIES

We consider n different EI values corresponding to traffic volumes x_j which were measured for year $j = 1, \ldots, n$, respectively. Thus, $I_j = I(x_j) = \frac{f(x_j)}{x_j}$. Then, the average energy intensity $\bar{I}_n$ is considering the total energy consumption and the total traffic volume summed up over the n years. In contrast, the (arithmetic) average of intensities leads to a different value – which is wrong, as illustrated in Figure 17.

$$\bar{I}_n = \frac{\sum_{i=1}^n f(x_i)}{\sum_{i=1}^n x_i} \neq \frac{1}{n}\sum_{i=1}^n I(x_i) = \frac{1}{n}\sum_{i=1}^n \frac{f(x_i)}{x_i} = \bar{\Sigma}_n \quad (88)$$

Note that also the harmonic mean $\bar{H}_n$ of the EI values is different from the average energy intensity $\bar{I}_n$ over the years.

$$\bar{I}_n = \frac{\sum_{i=1}^n f(x_i)}{\sum_{i=1}^n x_i} \neq \frac{n}{\sum_{i=1}^n \frac{x_i}{f(x_i)}} = \bar{H}_n \quad (89)$$

Limit 6 (Averages of Energy Intensities): EI values cannot be simply averaged.

TABLE 4. Glossary and abbreviations.

Term	Description
BPJ	Bit-per-Joule Efficiency
CADE	Corporate Average Datacenter Efficiency
CEF	Carbon Emission Factor
CI	Carbon Intensity
CNEE	Communication Network Energy Efficiency
COP	Coefficient of Performance COP
CPE	Compute Power Efficiency
CUE	Carbon Usage Effectiveness
CiE	Communication infrastructure Efficiency
CrEE	Consumption-related Energy Efficiency
CrEE	consumption-related energy efficiency
CrU	Consumption-related Uneffectiveness
DCIE	Data Center infrastructure Efficiency
DCeP	Data Center Energy Productivity
DPPE	Datacenter Performance per Energy
EC	energy consumption
EE	energy efficiency
EER	Energy Efficiency Ratio
EESF	Energy Eat and SLA Violation Factor
EI	energy intensity
EIS	energy-proportional ideal system
EPC	Energy Proportionality Coefficient
EPI	Energy Proportionality Index
ERE	Energy Reuse Effectiveness
ERF	Energy Reuse Factor
ESV	Energy Consumption and SLA violations
GEC	Green Energy Coefficient
ITEE	IT Equipment Efficiency
ITEU	IT Equipment Utilization
NPC	Normalized Power Consumption
NPUE	Network Power Usage Effectiveness
OrEE	Output-related Energy Efficiency
OrEE	output-related energy efficiency
OrU	Output-related Uneffectiveness
PUE	Power Usage Effectiveness
ROS	realistically optimal system
SEER	Seasonal Energy Efficiency Ratio
TEER	Telecommunications Energy Efficiency Ratio
WUE	Water Usage Effectiveness

5) AVERAGE POWER AND THROUGHPUT OVER SAME TIME FRAME

EI considers the energy consumption and the data volume over a particular time t. We can transform the EI and obtain the ratio of average power $P(x)$ (in W) and throughput $R(x)$ (in bps) over time t. Hence, the unit of EI is W/bps or equivalently J/bit, as also discussed in Section IV-A.

$$I(x) = \frac{f(x)}{x} = \frac{f(x)/t}{x/t} = \frac{P(x)}{R(x)} \quad (90)$$

Insight 7 (Power and Throughput): For computing the EI, the average power and throughput over a certain time can be computed – or the cumulated energy and volume over time.

D. SHORT-TERM AND LONG-TERM PERSPECTIVES

As we describe in Section II, the limited energy proportionality of networking devices prohibits the use of EI to estimate how energy consumption by a network device what change in response to varying level of traffic, because the linear EI function misses the offset idle consumption requires. There is an incongruence between a short-term and a long-term perspective on the network. Short-term perspective on the change of power consumption of a device relative to throughput could be described with an affine function $c + f(x)$. This would consider the baseline power consumption as fixed. However, when considering changes at the level of the entire network and how it evolves over longer term, as it coming to the case when sustainability is addressed, then fix baseline power consumption can be influenced, and the marginal effect on it is important to study.

In summary, constant EI must not be used to describe a change of power consumption relative to throughput on the level of an individual device, and estimating the long-term marginal change on the level of the entire network needs to take the change of baseline power consumption into account, and cannot be based on a snapshot of aggregate energy consumption and data volume for a single point in time. The same limits are also valid for the consumption- and output-related energy efficiency measures. A mathematical proof is omitted, but for energy-proportional reference systems the bit-per-joule efficiency as well as the output- and consumption-related EE agree, cf. Theorem 2.

VI. CONCLUSION AND DISCUSSIONS

Energy efficiency gains importance in the Internet and in communication networks in general. The article discusses energy efficiency metrics by focusing on energy intensity (EI), which measures energy consumption (EC) per traffic volume. However, using EI alone to predict the energy consumption is often inaccurate and wrong. A key concern is that the prediction of EC based on EI leads to significantly wrong results when the traffic is scaled up. Only in the case of (ideal) energy-proportional systems, the prediction is accurate; not in the case of real systems. To enable the application of evaluating the environmental benefits of optimisations, the engineering community needs to recognise the difference between the short and long-term perspective on the network, and how the interaction of increased energy efficiency of devices, growing demand for capacity, and system use interact. Improved modelling is the only way to avoid overestimating the benefits of reducing data volumes and the environmental impact from increasing data volumes for services. The article explores this issue, highlights limits and pitfalls, and provides relevant insights into the relation of EI to energy efficiency.

To be more precise, two generic metrics for energy efficiency are defined, that are the consumption-related efficiency η and the output-related energy efficiency ν. Those two measures relate a real system to an ideal reference system. Furthermore, the bit-per-Joule efficiency γ is analysed, which is the inverse of the EI. The relationships between the different EE measures are considered in general and in particular when using energy-proportional systems as ideal reference systems. As an important relationship, we identify that the metrics are identical $\eta = \nu = m\gamma$, where the constant m reflects the constant energy intensity of an ideal energy-proportional system. This also means that the EI is inversely proportional to energy efficiency in the case of an energy-proportional ideal reference system. This is an important relationship in practice. For example, a value of $\eta(x) = \nu(x) = 0.5$ means that the ideal system requires only half of the EC of the real system. It also means that the real system only processes half of the traffic volume of the ideal system. An energy-proportional ideal system is therefore a recommended reference system in practice.

Practical applications of the measures and their insights are demonstrated when benchmarking systems and when considering the value of the system's output. In particular, all measures can be utilized to benchmark the energy efficiency of two systems. We emphasize that the consideration of the value of the output of a system may be considered in the energy efficiency analysis instead of the traffic volume being processed. This may lead to significant differences and relevant insights in practice, as demonstrated on the example of power consumption and QoE of video streaming users. In practice, it is crucial to recognize that identifying optimal operational points or to benchmark systems is a multifaceted optimization challenge. While energy consumption and efficiency are significant, they represent only one aspect of the broader picture. Factors such as performance, quality of service (QoS), quality of experience (QoE), or resilience are equally important and must be considered.

Currently, an ultimate goal in 6G research is to enable zero-energy consumption. This means no energy is consumed when no traffic is generated or processed, e.g. by switching off a cell. Such energy-proportional systems are a design goal in 6G. But research in 6G requires significant R&D efforts to enable energy-proportional systems with energy consumption adaptations to the instantaneous traffic profile. Furthermore, frameworks for the quantification of KVIs are currently developed and provide a mean in defining a quantifiable value as output of a system.

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