Just Another Metric? Towards Optimizing Sustainability Across Multiple Network Components

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***Abstract*—This work will investigate how sustainability in Information and Communication Technology systems can be modeled, quantified, and optimized across users, communication networks, and data centers. Addressing the multi-dimensional and often conflicting nature of sustainability objectives, it explores the interplay between environmental impact, system performance, and user behavior. The work aims to develop metrics, models, and optimization approaches to capture system-level interactions, including sustainability–QoE trade-offs, network-level emission dynamics, and workload shifting in geographically distributed data centers. By integrating these perspectives, the work aims to provide a holistic perspective on sustainability-aware design and operation of future ICT systems.**

***Index Terms*—sustainability, green networking, data center sustainability, QoE and sustainability**

I. Introduction

Climate change is one of the most significant challenges of our time. Discourse often focuses on major emitting sectors such as transport, which accounted for 17 % of global greenhouse gas emissions in 2023 [1]. Less attention is given to sectors like Information and Communication Technologies (ICT), whose share of emissions is growing [2], [3]. However, ICT plays an ambivalent role: it both contributes to emissions and enables reductions in other sectors, e.g., by substituting travel with video conferencing [2]. This dual role makes sustainability in ICT a multi-objective optimization problem.

Networking research has traditionally focused on performance metrics such as throughput, latency, and reliability [4]. Adapting these existing optimization methods to sustainability is challenging, as environmental objectives are multi-dimensional and often conflict with service quality. Moreover, marginal performance gains increasingly show diminishing returns, raising the question of whether they justify high environmental costs. Trade-offs are further complicated by ICT's interconnected nature: optimizing one metric locally can shift burdens elsewhere, and multiple stakeholders, like users, network operators, and data center providers, have differing incentives. Limited data availability [5] further hinders the definition, validation, and evaluation of meaningful sustainability metrics, making system-level modeling highly challenging.

For that reason, this work aims to contribute to this research area by investigating sustainability and its complex interactions across multiple network parts. In particular, the work explores how sustainability metrics can be defined for different actors, how sustainability influences already known performance metrics, how different objectives interact, and where potential optimization pitfalls arise.

ISBN 978-3-903176-82-9 © 2026 IFIP

The remainder is structured as follows. Section II reviews the state-of-the-art and identifies key research gaps. Section III formulates the core research questions. Section IV presents the proposed methodology, and Section V concludes with an outlook on planned research.

II. State-of-the-Art

Research on ICT's environmental impact highlights its ambivalent role in sustainability. While ICT infrastructure consumes energy, early studies emphasize its positive effects on national economies, showing that increased ICT development can reduce a country's overall environmental impact [6], [7]. Empirical evidence suggests this relationship is complex and may be non-linear [7], [8]. Systematic reviews further note that quantifying ICT's total environmental impact is difficult due to heterogeneous data, methodological inconsistencies, and the absence of supportive economic policies [2].

While research finds relative consensus, that increasing ICT development has more positive benefits, than negative, the ever increasing demand and infrastructure expansion, makes ICT itself a major contributor to greenhouse gas emissions. Therefore, research focus shifts to reducing the negative impacts of ICT infrastructure, particularly data centers and communication networks. Data centers represent a rapidly growing share of global electricity consumption due to increasing demand for cloud services and digital applications [9]. While improvements in hardware efficiency and virtualization have reduced energy consumption per computation, the overall impact remains uncertain because increasing workloads may offset efficiency gains. Moreover, analyses often neglect life-cycle effects such as manufacturing and disposal and fail to quantify the marginal per computation or per user impact [5].

In communication networks, sustainability research traditionally focuses on improving the energy efficiency of networking equipment and protocols. Several metrics have been proposed to evaluate device-level efficiency. Riekstin et al. [10] highlight that most metrics in this context focus on energy consumption and performance in terms of useful work, with less focus on greenhouse gas emissions, and no focus on time as performance component, e.g., as in delay. However, even though this is researched for some years now, there is still no widely accepted framework for evaluating sustainability across entire network systems. Existing metrics often focus on energy consumption, efficiency, or intensity, while broader environmental impacts and system interactions, and especially marginal impact of additional traffic, and increased infrastructure expansion, remain insufficiently addressed [11]. At the same time, the development of such metrics is hindered by limited data availability and a lack of standardized measurement methodologies [9].

Beyond component-level analyses, the role of the end-user has received relatively little attention, although user decisions strongly influence service demand and traffic generation. Users are central beneficiaries of network systems and ultimately where value is created. However, their growing concerns for sustainability might influence the relationship between service quality and their Quality of Experience (QoE), but remains insufficiently explored [12].

This state-of-the-art overview highlights several important research gaps: First, reliable data on the environmental impact of ICT infrastructure is still limited. Second, existing sustainability metrics lack standardization and often capture only partial aspects of environmental impact. Third, most studies analyze individual components such as networks or data centers in isolation, while system-level interactions remain insufficiently explored. Finally, the role of user behavior needs further assessment.

III. Research Questions

Building on this, this work investigates sustainability in ICT systems from a system-level perspective, focusing on interactions between users, networks, and data centers to identify meaningful metrics and integrate sustainability into system design. The research question guiding this work is:

- **RQ:** How can sustainability in ICT systems be modeled, quantified, and optimized while accounting for user, network, and data-center level effects?

To structure the work into manageable research tasks, this central question is further sub-divided into several research questions, each addressing a component of the overall system.

A. User Perspective

The first part focuses on the user perspective, examining how sustainability considerations affect user behavior and perceived QoE. Video streaming is selected as a representative use case, as it accounts for a large share of global Internet traffic [13]. Consequently, one research question from the user's perspective is formulated:

- **RQ1:** Are users willing to compromise on streaming quality to reduce the associated carbon emissions and how does this change existing QoE models?

B. Network Perspective

The second part examines the environmental impact of communication networks, focusing on how traffic patterns and infrastructure development affect sustainability. Given the heterogeneity of this field, including diverse access technologies, use cases, and network equipment, preliminary, high-level research questions are formulated. Special emphasis is on analyzing time-varying traffic, which interacts with renewable energy availability, and on quantifying the marginal impact of additional traffic.

- **RQ2.1:** How can the environmental impact of communication networks, and the marginal impact of additional traffic, be quantified and analyzed, considering traffic patterns, network infrastructure, and power consumption?
- **RQ2.2:** How do evolving traffic demand, user behavior, and network expansion influence the long-term sustainability of networks?

C. Data Center Perspective

The third and final part examines data centers, exploring how sustainable operation impacts both networks and users. As a first step, geographically distributed data centers and workload-shifting strategies are investigated, considering how computation can be aligned with renewable energy availability while accounting for interactions with network traffic, congestion, and service quality.

- **RQ3.1:** How can geographically distributed data centers and workload-shifting strategies be leveraged to reduce CO_2 emissions?
- **RQ3.2:** Which metrics and models are suitable for assessing these system-level sustainability effects?

IV. Selected Methodology

To address these research questions across users, networks, and data centers, this section outlines the methodology chosen to investigate sustainability in ICT systems.

A. User Perspective

The user perspective is critical for understanding ICT sustainability, as user behavior directly shapes network traffic and service demand, and thus environmental impact. Decisions are influenced by multiple factors, including service quality, usability, and awareness of sustainability, which may alter the traditional relationship between Quality of Service (QoS) and QoE. Existing literature lacks studies quantifying sustainability as a factor influencing QoE.

To address RQ1, the goal is to conduct global crowdsourced user studies on video streaming, a major contributor to Internet traffic [13]. Participants first evaluate short video clips at fixed resolutions to establish baseline QoE. They then watch videos with adjustable playback resolution and CO_2 emission information, allowing analysis of whether sustainability information influences resolution choices and perceived QoE. This approach enables quantification of user willingness to trade service quality for reduced emissions. Based on this, the traditional QoE models will be extended with sustainability as an influencing factor.

Additionally, user interaction patterns, particularly in short-form video platforms, will be analyzed to assess their impact on network traffic and resulting emissions. By linking interaction behavior to data transfer and environmental footprint, the study examines how user behavior contributes to the overall sustainability of digital services, further addressing RQ1.

Several challenges are expected in this investigation. The values displayed for CO_2 emissions are likely to strongly influence user choices, potentially biasing results. However, accurately estimating the CO_2 footprint of a single video stream is difficult due to missing data, lack of standardized methodologies, and limited per-user granularity. These limitations must be considered when interpreting results and may necessitate further studies.

B. Network Perspective

The communication network connects users and data centers through diverse devices, links, and protocols. While energy efficiency of individual components is well studied, system-level strategies must consider traffic distribution, operational choices, and sufficiency-oriented approaches, where adequate service quality is balanced with minimal resource use.

To address RQ2.1, networks are modeled using synthetic topologies and device power consumption models. Energy use is converted into CO_2 emissions using time- and location-dependent electricity carbon intensity, allowing evaluation of different assumptions. The approach may also enable assessment of marginal emissions from additional traffic by incrementally introducing new service requests and measuring the resulting changes in energy use and emissions.

Furthermore, the modeling framework can be used to explore how increasing traffic demand influences the sustainability of network infrastructures over time. In particular, the analysis aims to investigate whether growing demand may trigger infrastructure expansion, such as additional links or network devices, and how such expansions affect long-term sustainability, effectively addressing RQ2.2.

Key challenges include limited traffic and power data, time-varying carbon intensity, and uncertainties in user behavior and infrastructure growth assumptions. Additionally, the heterogeneity of use cases, data traffic, devices, and technologies in the network make a holistic investigation difficult, and may necessitate a bottom-up approach instead.

C. Data Center Perspective

Data centers are a key component of ICT systems, providing computing and storage resources. Beyond improving individual data center efficiency, we adopt a holistic perspective, examining how shifting computational workloads across geographically distributed data centers can enhance sustainability and influence other system components. Workload relocation can better align energy use with renewable availability but may also increase network traffic and affect service quality.

To address RQ3.1, a data-driven modeling approach is employed. Real-world measurements of renewable generation, electricity load, and carbon intensity are combined with geographically distributed data center models to simulate workload shifting and evaluate potential CO_2 reductions. Spatial workload allocation is formulated as an optimization problem prioritizing renewable energy utilization. In the process, appropriate metrics and modeling approaches for assessing sustainability effects, including network impact, congestion, and service quality will be identified to address RQ3.2.

Expected challenges include limited data on data center energy consumption and equipped devices, and models for correctly applying time-varying and localized CO_2 intensity.

V. Outlook

To this end, the work ahead focuses on systematically analyzing sustainability across the ICT system, progressing from users to networks to data centers, and integrating insights across these layers. In the near term, user studies will quantify how behavior and awareness influence QoE, identifying trade-offs between perceived quality and environmental impact. Building on these findings, the network layer will be analyzed to assess how traffic patterns, marginal emissions, and infrastructure expansion interact with evolving user behavior. For this step, the appropriate scope and concrete models still need to be defined, e.g., focusing on a specific use case or access technology. For data centers, initial work has modeled geographic workload shifting theoretically. The next step is to incorporate a detailed network model to evaluate negative effects on traffic and service quality.

Acknowledgments

This work was partly funded by the German Federal Ministry of Research, Technology and Space, Grant 16KIS2282 “SUSTAINET-Advance”, of the University of Würzburg.

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