A Greener Experience: Trade-offs between QoE and CO_2 Emissions in Today's and 6G Networks

Tobias Hoßfeld, Martín Varela, Lea Skorin-Kapov, Poul E. Heegaard

***Abstract*—While users of Internet multimedia services demand high Quality of Experience (QoE), meeting these demands results in energy consumption along the service delivery path, from the end user's device, through the network to the service infrastructure (e.g., in a cloud). This energy consumption typically implies carbon dioxide (CO_2) emissions, which are a primary driver of climate change. One contribution of this article is to quantify and illustrate the trade-off between the QoE of video streaming services and CO_2 emissions. Kleinrock's power metric from queuing theory is applied to find operational points and recommended video bitrates of the QoE–sustainability trade-off. Furthermore, considering that networks and service delivery infrastructures are still in the process of transitioning towards "green energy" consumption, we investigate the impact of "green users" accepting certain quality degradations so as to reduce CO_2 emissions. Our discussions focus on two aspects: Is it more relevant to focus on green user behavior or green networking technology today and in the future in year 2030? What are the implications of solution approaches on the networking and communications technology?**

I. "GREEN QOE" SERVICE AND NETWORK MANAGEMENT

Rapid developments in the communications and networking communities are paving the way for widespread use of Internet multimedia services, with both service providers and network operators striving to meet end user demands for high Quality of Experience (QoE). This commonly involves finding solutions for maximizing QoE, while supporting cost-effective network and system operations. Going beyond cost efficiency, the urgent need to address climate concerns has raised awareness among governments, service providers, and the general public about meeting sustainability goals and reducing CO_2 emissions when using Internet services. *Green energy* will eventually be commonplace, as providers move to green sources of energy, and more energy-efficient technologies become available. However, with networks and service delivery infrastructures still in the process of transitioning towards green energy consumption, challenges arise with respect to finding solutions for reducing CO_2 emissions. Notably in 6G [1], sustainability has become a core aspect of future networks' development towards *green networks*. This is however still years in the future and some concrete actions could be taken sooner, at least as stop-gap measures.

We address the challenge of reducing the CO_2 emissions associated with Internet multimedia service delivery by investigating a *user-centric* approach. Stemming from the QoE modeling and management domains, we propose to exploit knowledge related to end user's quality perception and investigate to what extent energy requirements can be reduced (both in terms of compute and network resources), without adversely impacting user experience. An example would be limiting streaming video bitrates to levels sufficient for meeting end user QoE requirements, rather than exceeding such bitrate levels in pursuit of diminishing QoE gains, resulting in superfluous energy consumption [2].

To this end, we introduce the notion of a *green user* as a user who incorporates awareness of energy consumption into their overall QoE ratings, i.e., for the same amount of allocated resources (such as bitrate during video streaming), they will provide a higher QoE rating than a "non-green" user. Green users may be willing to make a slight sacrifice in QoE to decrease their CO_2 footprint. As a consequence, a *green QoE model* is required to properly capture the QoE of green users. For network and service management (NSM), such QoE models are then used as constraints in resource allocation, e.g., aimed at minimizing bandwidth usage, subject to providing at least acceptable quality for end users.

To illustrate potential trade-offs between QoE and sustainability, we use existing models from literature i) on energy consumption and CO_2 emissions when running Internet services, and ii) on QoE for video streaming, which we extend towards a green QoE model. While various approaches may be taken in solving the multi-objective optimization problem of maximizing QoE while minimizing CO_2 emissions, for illustration purposes we apply a common method from queuing theory (Kleinrock's power metric) to derive good operational points. This will answer, from an objective point of view, what would be a good target video bitrate for viewing, relating QoE and sustainability. Our aim is thus to motivate the joint exploitation of QoE models and energy consumption models so as to drive *"Green QoE"* NSM. We further consider the relative impact that green users vs. green networks have on CO_2 emissions. We address the question of whether it is more relevant to focus on a) empowering green user behavior or b) green networking technology today and in the future. Currently, users are not able to decide themselves for greener usage of Internet services and we argue for empowering green users. Finally, we discuss practical implications and potential technical realizations in the context of meeting 6G human-centricity and sustainability goals.

T. Hoßfeld is with the University of Würzburg, Chair of Communication Networks, Germany. tobias.hossfeld@uni-wuerzburg.de

M. Varela is with Profilence, Oulu, Finland. martin@varela.fi

L. Skorin-Kapov is with the University of Zagreb, Faculty of Electrical Engineering and Computing, Croatia. lea.skorin-kapov@fer.hr

P.E. Heegaard is with NTNU, Trondheim, Norway. poul.heegaard@ntnu.no

II. GREEN USERS AND GREEN QOE MODEL

We identify two types of users: *high-quality (HQ) users* that expect the highest quality possible given available resources, and *green users* who incorporate awareness of energy consumption into their overall QoE rating and are satisfied with somewhat lower objective quality levels. Note that the latter need not be purely motivated by an environmental goal, but also because (especially mobile) users value preserving battery life [3], with lower bitrates contributing to meeting this objective. While users may be willing to make trade-offs on quality for "greener" services, the work in [4] has shown that most users are not aware of the environmental impact of digital services, and hence informing and educating users is also necessary for them to adopt a "greener" posture.

In terms of QoE modeling, the willingness of *green users* to sacrifice some quality to reduce their carbon footprint can be considered an *advantage factor*, as done for example in the E-Model for voice quality of mobile users. The green user can thus be equally satisfied with lower video bitrates (and therefore possibly lower perceptual quality) than the HQ user.

Subjective user studies show a logarithmic relationship between video bitrate and Mean Opinion Scores (MOS). This logarithmic behavior is a common observation in QoE models [5] and related to the Weber-Fechner law from psychophysics. In [6], the authors provide the parameters of a logistic regression of MOS scores depending on the video bitrate, which is illustrated in Figure 1 as 'HQ user'. A maximum theoretical MOS of 5 (excellent quality) is reached for a bitrate of 14:5 Mbps according to [6].

For a *green user*, we adjust the logarithmic QoE model and introduce a *greeness factor* as an advantage factor, assuming users rate lower video quality with a higher score if they know it saves energy. Hence, the maximum MOS of a green user is reached for 14:5 Mbps= . Figure 1 compares the QoE of the HQ and the green user. This model is used later in the evaluation to investigate the QoE model sensitivity to our conclusions in terms of recommended video bitrates taking into account the MOS–CO_2 trade-off. In our results, we use $= 1$ and $= 2$ for the HQ users and the green users, respectively. Hence, the maximum MOS of 5 is reached for 14:5 Mbps and 7:25 Mbps, respectively.

III. CO_2 EMISSIONS FOR INTERNET SERVICE DELIVERY

Understanding the footprint of Internet service delivery is a challenging task, as the total energy consumption may be modeled as the sum of energy consumption across different components along the service delivery path: end user devices, access networks, core network, data center, and Internet service infrastructure.

Energy consumption models thus typically work on a macroscopic level. For the network access, annual traffic volume and the average annual electricity usage is considered. This yields a macroscopic view, taking into account different hardware equipment, and provides the electricity intensity (in kWh/GB). In a similar way, the electricity used per traffic unit for data centers is derived based on annual reports. Similarly, for consumer devices, the electricity usage is related to the usage time and provides the electricity intensity (in kWh/day). In addition, the electricity production numbers and the lifetimes of hardware equipment and devices are modeled.

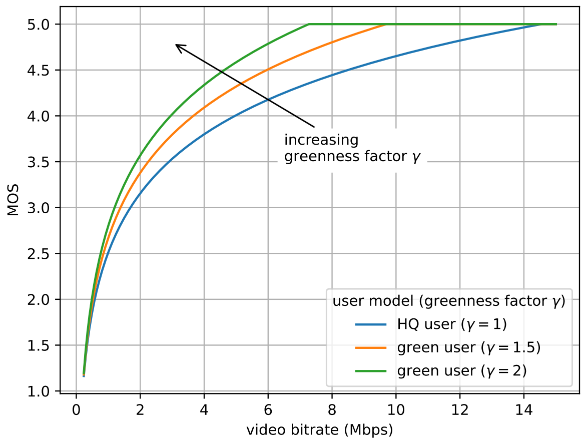

Fig. 1. QoE model of the high-quality (HQ) user and the green user. The provided video bitrate to MOS mapping function considers the minimum bitrate $x_1 = 200\,\mathrm{kbps}$ (yielding MOS 1) and maximum bitrate $x_5 = 14{:}5\,\mathrm{Mbps}$ (yielding MOS 5). The greenness factor considers that a green user is satisfied with maximum bitrate $x'_5 = x_5 =$ yielding MOS 5. We extend the logarithmic QoE model in [6] for the green QoE model: $f_\gamma(x) = \frac{4}{\log x'_5 \quad \log x_1} \log x + \frac{\log x'_5 \quad 5 \log x_1}{\log x'_5 \quad \log x_1}$.

In this article, we focus on the use stage and the related energy consumption and CO_2 emission. We use two different energy consumption models: the Shift model [7] and the model by Andrae and Edler [8]. The latter also considers that there will be an improvement in the electricity efficiency of devices, access networks and data centers in the future. Thereby, efficiency improvements from the past are used for the prediction of future energy efficiency. In particular, parameters for the energy consumption model for 2020 ('AE 2020') and the year 2030 ('AE 2030') are provided. The 'Shift' model also provides the parameters, published in 2019, but their estimations are more pessimistic than [8], see Figure 2. The two different models allow to investigate model robustness concerning our conclusions.

Total energy consumption is a linear model of the service usage time and the data traffic volume, with the electricity intensity parameters for the different components as suggested by [7] and [8]. The parameters are specified in Table I. Note that we use the expected energy consumption in [8], also suggesting a best and worst case scenario for the prediction. For the energy consumption of a device, we use the parameters from the Shift project for a laptop in our numerical results. Furthermore, we use Wi-Fi access in the home network and fixed Internet access. The total CO_2 emission is a linear model of the total energy consumption. The parameters are taken from [7] and provided for different regions in Table I. Later, we use the CO_2 intensity for the European Union (EU).

TABLE I

ELECTRICITY INTENSITY FOR NETWORKS AND DATA CENTERS PROVIDED BY [8] (YEAR 2010–2030) AND BY THE SHIFT PROJECT [7]. CARBON INTENSITY FOR DIFFERENT COUNTRIES BY [7].

Energy intensity Component	year 2010 (kWh/GB)	year 2020 (kWh/GB)	year 2030 (kWh/GB)	Shift Project (kWh/GB)
FAN wired	0.50	0.11–0.28	0.061–0.17	0.429
FAN Wi-Fi	0.36	0.07–0.17	0.014–0.10	0.152
Mobile access	6–15	0.047–1.04	0.002–0.048	0.884
Data centers	0.13–0.14	0.027–0.085	0.014–0.051	0.072
Device	smartphone		laptop	
Energy intensity	0.155 kWh/day		0.460 kWh/day	
CO_2 intensity (kgCO2e/kWh)	EU 0.2759	US 0.4932	China 0.6810	World 0.5190

Countries are increasingly meeting growing energy demands with the use of renewable energy sources - primarily hydro, solar, and wind energies. However, while renewable energy generally has low CO_2 emissions, to be considered truly "green", the adverse effects of such technologies in terms of both environmental impact and carbon emissions would need to be mitigated [9]. In this article, we highlight that we refer to *green energy* as that which has zero emissions, and refrain from delving deeper into an analysis of different types of renewables and potential emissions. Furthermore, we later analyze the impact of the ratio of green energy on the total CO_2 emissions. In particular, the *ratio of green energy of the network operator* is defined as the fraction of emissions hypothetically eliminated from today's network while keeping energy consumption the same. Note that the CO_2 emissions of both device and data center are not changed, since our analysis addresses whether greening the networking infrastructure or empowering green users is more beneficial in the transition towards clean energy.

IV. VIDEO STREAMING USE CASE: GREEN USERS AND GREEN NETWORKING

As a concrete use case, we consider video streaming and its impact on energy consumption and CO_2 emission. We use concrete numbers obtained from the streaming of *Hawaii Five-O* TV series with an average duration of 42 min per episode. Each episode is streamed to users at a chosen video bitrate, thus determining the QoE of the user. We differentiate between HQ and green users with the corresponding greenness factors = 1 and = 2, respectively. Average video bitrate results in a certain amount of data traffic per episode and is considered as input for the energy consumption and CO_2 emission model.

Our aim is to provide numerical results that give insights to the following research questions: *What is the trade-off between QoE and CO_2 emission? How can an optimal operational point be derived (i.e., video bitrate) for the multi-criteria decision problem QoE vs. CO_2? How much reduction in CO_2 emission can be achieved by a green user as compared to a high-quality user? How much reduction in CO_2 emission can be achieved by moving towards a green network (i.e., by increasing the ratio of green energy consumption as compared to non-green energy)?* Finally, we also investigate what is the relative impact on the reduction of CO_2 emissions of green user behavior as compared to green networking?

A. Trade-off between QoE and CO_2 Emission

There is an obvious trade-off between the QoE and the CO_2 emission. Higher video bitrates lead to higher MOS values and user satisfaction – which is a nonlinear (logarithmic) relationship. At the same time, the CO_2 emission linearly rises with the video bitrate. Figure 2 quantifies the trade-off for the different energy models for the HQ user and green user, respectively. In order to reach excellent QoE (MOS 5), much more CO_2 emissions are generated as compared to good QoE (MOS 4): the CO_2 emissions are more than doubled for any of the energy models and both user types.

The shaded areas indicate the amount of CO_2 emission reduced by the green user as compared to the HQ user. To achieve good or better QoE (corresponding to 4 and 5 on a 5-pt MOS scale) for a HQ user, an increase of 150% is observed of the CO_2 emission compared with a green user. Similar behavior is observed for low bitrates.

Fig. 2. Trade-off between QoE and CO_2 emission for the HQ user and the green user, portrayed across three different energy models. Optimal video bitrates according to Kleinrock's power metric are identified, and resulting MOS and CO_2 emission is marked with a diamond (HQ user) or square (green user). The filled area presents the results for 2 [1; 2].

B. Target Operational Point for the Trade-off

From the NSM perspective, the question arises as to what would be a target operational point, i.e., video bitrate, considering the MOS-CO_2 trade-off. On the one hand, the QoE of users should be maximized, while on the other hand CO_2 emissions should be minimized. To decide the optimal video bitrate of the Pareto front in Figure 2, various multi-criteria decision methods (MCDM) can be used. In this article, for illustration purposes, we use the Kleinrock [10] *Power* metric which is an (one-dimensional) optimization metric to identify the knee of the MOS–CO_2 curve. The power metric is the ratio of `goodness' (i.e. QoE) divided by `badness' (i.e. CO_2

emission). The optimization of power leads to a trade-off between maximizing `goodness' (i.e., QoE) while minimizing `badness' (i.e., CO_2 emissions). In practice, it may be relevant to specify some constraints, e.g., that the QoE in terms of MOS is at least 3.5. Some MCDM approaches natively integrate value constraints in the multi-criteria problem statement as well as in the decision making process, such as ISOCOV `Ideal SOlution with COnstraint on Values'. We note that Kleinrock's power metric can also take into account such constraints. For example, instead of using the MOS values y, the values can be shifted by 3.5, or a Heaviside function can be used to eliminate solutions with MOS less than 3.5, i.e., $h(y - 3.5)$.

For the numerical results given in this article, we consider the MOS as being normalized to $[0;1]$ as `goodness' $G$ and the $CO_2$ emission as `badness' B. Thereby, despite the CO_2 emission from service usage, an additional constant offset of 0.05 kgCO2e related to the production CO_2 emission is used, e.g., to integrate green energy (resulting in zero emissions) in the network provider's infrastructure. We then compute the ratio G/B and derive the maximum to identify the recommended video bitrate according to Kleinrock's approach.

Figure 3 shows the optimal video bitrate depending on the ratio of green energy of the network operator. Note that we do not change the energy consumption by the device and the data center. The numerical results lead to the following observations: a) We see that a “greener” network (i.e., with a higher ratio of green energy as compared to non-green energy) will result with higher optimal operational video bitrates, b) The same is true for more energy efficient networks in the future (AE 2030) as compared to today's energy efficiency (AE 2020), c) When comparing green and HQ users, we observe that identified optimal video bitrates are lower for the green user than for the HQ user. This is especially obvious for future green networks (AE 2030): much higher video bitrates are identified as optimal, since the corresponding CO_2 emissions are much lower. The practical deployment scenarios to trade-off between MOS and CO_2 are discussed later.

C. CO_2 Emission for Optimal Video Bitrates

Next, we consider the CO_2 emissions as calculated for the optimal video bitrates from Figure 3. The CO_2 results are provided in Figure 4 for the HQ and the green user depending on the ratio of green energy of the network operator.

The green user clearly reduces the amount of CO_2 emissions, also for the identified operational video bitrates. The ratio of green energy leads to a significant reduction of the CO_2 emissions for the HQ and the green user. This reduction is especially visible for the Shift model and the AE 2020 model, reflecting the current situation of energy consumption in the Internet. For the energy efficient networks of the future (AE 2030), the CO_2 reduction due to the ratio of green energy is smaller for the HQ user than for the green user.

D. Conclusions for Current and Future Efforts

Finally, we aim to answer if it is more relevant that (a) the user becomes greener (i.e., is satisfied with lower video bitrates), or (b) the network becomes greener?

Fig. 3. Kleinrock's approach is used to determine the optimal video bitrate. The Power metric is the ratio between MOS and CO_2 emissions. Its maximum identifies the suggested video bitrate.

Fig. 4. The CO_2 emissions for the optimal video bitrates (see Figure 3) are calculated.

Figure 5 considers the relative difference of the CO_2 emissions in Figure 4 between the HQ user and the green user. In today's Internet, this will save a significant amount of CO_2. However, the greener the network becomes, the green user does not result in an additional CO_2 reduction. In fact, the relative reduction is slightly decreasing, except for AE2030 where the reduction increases when the green user reaches the maximum MOS when more than 60% green energy is used.

Next, we analyze the CO_2 emission reduction due to green energy. To this end, we calculate the CO_2 reduction of the HQ user for a ratio x of green energy relative to the CO_2 emission for the HQ user without green energy. It can be seen that for today's Internet and energy efficiency (AE 2020, Shift model) the greener network leads to a big CO_2 reduction. Especially, if 20%-30% green energy is used by the network operator, the relative CO_2 reduction due to green network is larger than the reduction due to green users. Hence, we conclude that research and development should be aimed towards driving increasingly green networks, as can already be observed in the context of both network deployments and current 6G research activities.

An interesting observation is that with the move towards greener networks (see results for AE 2030), the decision by the user to be green has more relative importance and yields higher CO_2 reduction, since the network is not generating significant CO_2 emissions anyway. Hence, it is nevertheless important a) to raise awareness of users on their CO_2 emissions and b) to empower users and provide them with the option of accessing Internet services in a green manner.

Fig. 5. Reduction of CO_2 emission due to green user (solid lines) and due to green energy in networking (dashed line). The following observations are marked in the figure: (U1) The relative CO_2 reduction of green users compared to HQ users is about 5% without green energy in today's and future networks. (U2) In future networks (AE 2030), the relative CO_2 reduction due to green users is about 25%. (N1) In today's networks (AE 2020, Shift), green energy may reduce about 35% of CO_2 emissions. (N2) In future networks (AE 2030), green energy may reduce about 25% of CO_2 emissions.

V. DISCUSSIONS AND IMPLICATIONS

Our results indicate that awareness of CO_2 emissions and empowerment of users to reduce CO_2 emissions are crucial in the transition phase towards green networks. We discuss how this can be realized in the short term, looking at the implications for the networking architecture, and especially 6G. We look both at the user-related aspects, and the technical ones related to networks and services.

A. Empowering Users

The exploratory study [4] investigates the digital carbon footprint awareness among digital natives. Their results indicate that users are not aware of the environmental impact of digital applications and Internet services. A reason behind this is a lack of understanding how these Internet services are implemented, what is the underlying infrastructure and the required processes (e.g., encoding and streaming videos), and what is the resulting energy consumption and carbon footprint. To raise awareness among users, there are already plugins in browsers or smartphone apps available which give insights on where energy is consumed and what this consumption means in terms of emissions, e.g., Carbonalyser which is based on the Shift project [7]. Extending these types of indicators to be more pervasive, and possibly directly integrated into relevant platforms (e.g., browsers, or mobile OSs) would help to further educate users, and possibly shape their behavior.

The qualitative study in [4] also provides results on the willingness of users to make compromises considering the usage of Internet services. Their results show that while users seem to be willing to make compromises, the impact of these compromises needs to be made clearly visible to them. Some sort of “greenness indicator”, showing the impact on CO_2 emissions or battery life, for different app / service settings could be a way to implement this. For example: “This movie will use approx. 2 GB of data in HD quality and will generate y CO_2 emissions (comparable to driving x km by car).” Such statements can aid users in making informed decisions. Just offering a “green tariff” to subscribers might not be sufficient, but rather it would be more effective to demonstrate the concrete impact to users. This will be important for any user choice on trading off QoE vs. sustainability. One step further is the idea of “carbon credits” to summarize the aggregated CO_2 emissions over time, e.g., during a month. Users could purchase more carbon credits if exceeded during a month – similar to purchasing additional data volume. Additional research is required to investigate (i) if users would be willing to pay for extra carbon credits or (ii) if the concept of carbon credits and a free, non-monetary user request for further carbon credits (“Please click if you need further carbon credits.”) would be sufficient to raise user awareness and lead to changes in their behavior, e.g., by accepting lower qualities to lower CO_2. While both technical and business realization aspects are open research topics, one option would be for operators/service providers to offer users service level agreements (SLAs) or experience level agreements (ELAs) that incorporate both carbon credits and costs to set customer service levels.

The willingness of users to take sustainability into account implies that empowering users to become “green” is a promising step in the transition phase to the time when green networks are ubiquitous. Users may be willing to reduce their QoE adequately to reduce energy consumption. This could be natively integrated into e.g., video players, or better yet, at the platform level, so that users are able to select a green mode or to specify a maximum video bitrate. However, for automated operation (green mode), the player needs additional information, such that it may identify reasonable operational points based on the energy consumption, ratio of green energy of the operators, and the resulting CO_2 emissions. However, if this is implemented on the client side (e.g., directly into the player, via some sort of plugin, or at the platform level), information about the concrete impact of different settings needs to be made available by service and network providers. This has already been done, see data sources of the models we used [7], [8]. However, possibilities for direct information exchange could speed up the development, as discussed below.

B. Networking Architecture and 6G

As our numerical results indicated, the usage of green energy will have a large impact on CO_2 emissions. We expect that green energy as well as energy efficient networking and communications will be used by operators in the future. However, [11] identifies the rebound effect as critical, e.g., increasing energy efficiency results in driving up energy consumption. Hence, empowering consumers to achieve concrete goals such as “2T CO_2/Year/Person” is important to avoid needless over-consumption.

Even if we expect that future networks will operate (partly) with zero-waste and zero-emission technologies, as envisioned by 6G [1], there will be a transition phase. We recommend that information about CO_2 emission (e.g., taking into account lifecycle assessment of devices) as well as energy consumption and the emerging CO_2 emission during operations, should be part of the management information base (MIB) for NSM. In [12], an excellent survey is given on metrics and measurement tools for sustainable distributed cloud networks which are the basis for Internet services. They also discuss RFC 7461 “Monitoring and Control MIB for Power and Energy”. In our opinion, this should be enriched with CO_2 emissions as well as static information about life cycle assessment parameters. Such input can then be utilized within the network or by applications to derive operational points towards “Green QoE” NSM.

In 6G, key value indicators (KVIs) go beyond key performance indicators (KPIs) in order to represent the dimensions of impact such as sustainability [13]. In that sense, Kleinrock's power metric with our notion of `goodness' (QoE) and `badness' (CO_2 emissions or energy consumption) can be seen as a concrete KVI. In practice, however, it is challenging to measure QoE and CO_2 emissions.

C. Interaction and Cooperation

A crucial point for holistic NSM is the information exchange between stakeholders. In the context of QoE management, different approaches for over-the-top (OTT) and ISP interactions have been discussed [14], such as: application-layer traffic optimization (ALTO), the collaboration interface between network and application (CINA) for P2P networks, or server- and network-assisted DASH (SAND) for dynamic adaptive streaming over HTTP (DASH). In particular, native interfaces offering access to CO_2 values (or an abstracted sustainability index) may be offered, e.g., by ALTO, which is then utilized by (video) service providers.

A detailed survey on QoE monitoring and QoE management approaches and how they are integrated in the networking architecture landscape is given in [15]. Finally, novel QoE models may incorporate context factors such as energy and CO_2 directly. Currently, widely utilized QoE models are mainly limited to perceptual dimensions such as video quality. In the future, operators may need to report energy and CO_2 values to meet sustainability goals from society and regulators.

VI. CONCLUSIONS

The delivery of Internet multimedia services such as video streaming yields a trade-off between QoE and energy consumption as well as the resulting CO_2 emission. We illustrate a potential solution for solving the multi-objective optimization problem, by applying Kleinrock's power metric from queueing theory to derive good operational points. As a case study, we consider video streaming and combine existing QoE, energy consumption, and CO_2 emission models to identify recommended video bitrates for viewing. In particular, we compare the relevance of green users and green energy for operating the network infrastructure in terms of CO_2 emissions. Both current and future networking technology with improved energy efficiency are investigated. Our numerical results indicate that today's research and development should be aimed towards driving increasingly green networks, as can already be observed in the context of both network deployments and current 6G research activities. Still, awareness of the environmental impact of Internet users and their empowerment to become green users are important, especially in the transition phase towards green networks. To this end, we discuss today's possibilities to empower users, as well as the implications for the networking architecture for “Green QoE” service and network management.

REFERENCES

[1] S. Yrjölä, P. Ahokangas, and M. Matinmikko-Blue, “Sustainability as a Challenge and Driver for Novel Ecosystemic 6G Business Scenarios,” Sustainability, vol. 12, no. 21, 2020.

[2] B. O. Turkkan et al., “GreenABR: Energy-Aware Adaptive Bitrate Streaming with Deep Reinforcement Learning,” Proceedings of the 13th ACM Multimedia Systems Conference, 2022.

[3] S. Ickin, K. Wac, M. Fiedler, L. Janowski, J.-H. Hong, and A. K. Dey, “Factors influencing quality of experience of commonly used mobile applications,” IEEE Communications Magazine, vol. 50, no. 4, 2012.

[4] V. Gnanasekaran, H. T. Fridtun, H. Hatlen, et al., “Digital carbon footprint awareness among digital natives: An exploratory study,” in Norsk IKT-konferanse for forskning og utdanning, 2021.

[5] P. Reichl, S. Egger, R. Schatz, and A. D'Alconzo, “The logarithmic nature of QoE and the role of the Weber-Fechner law in QoE assessment,” in 2010 IEEE Int. Conference on Communications. IEEE, 2010.

[6] J. P. Lopez, D. Martin, D. Jimenez, and J. M. Menendez, “Prediction and Modeling for No-Reference Video Quality Assessment Based on Machine Learning,” in 14th Int. Conference on Signal-Image Technology & Internet-Based Systems (SITIS). IEEE, 2018.

[7] The Shift Project, “Lean ICT: Towards Digital Sobriety,” directed by Hugues Ferreboeuf, Tech. Rep., 2019, last accessed: August 2022. [Online]. Available: https://theshiftproject.org/en/article/lean-ict-our-new-report/.