

A Greener Experience: Trade-offs between QoE and CO₂ Emissions in Today’s and 6G Networks

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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 (CO₂) 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions associated with Internet multimedia service delivery by in-

vestigating 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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.

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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 *greenness factor* γ 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 $14.5 \text{ Mbps} / \gamma$. 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–CO₂ trade-off. In our results, we use $\gamma = 1$ and $\gamma = 2$ 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. CO₂ 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.

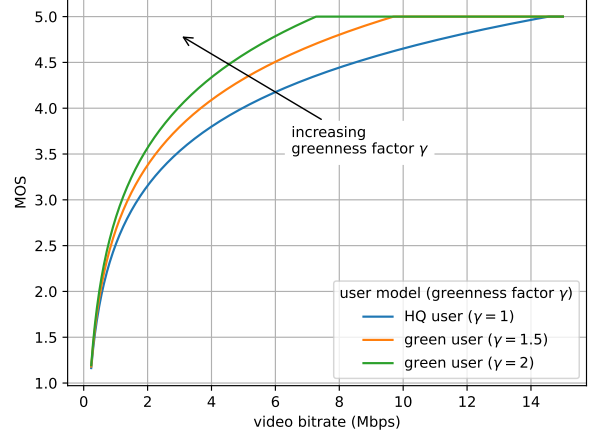


Fig. 1. QoE model of the high-quality (HQ) user and the green user. The provided video bitrate to MOS mapping function considers the minimum bitrate $x_1 = 200 \text{ kbps}$ (yielding MOS 1) and maximum bitrate $x_5 = 14.5 \text{ Mbps}$ (yielding MOS 5). The greenness factor γ considers that a green user is satisfied with maximum bitrate $x'_5 = x_5 / \gamma$ yielding MOS 5. We extend the logarithmic QoE model in [6] for the green QoE model:

$$f_\gamma(x) = \frac{4}{\log x'_5 - \log x_1} \log x + \frac{\log x'_5 - 5 \log x_1}{\log x'_5 - \log x_1}.$$

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.

In this article, we focus on the use stage and the related energy consumption and CO₂ 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 CO₂ 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 CO₂ 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 Energy intensity	smartphone 0.155 kWh/day		laptop 0.460 kWh/day	
CO ₂ intensity (kgCO ₂ e/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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 $\gamma = 1$ and $\gamma = 2$, respectively. Average video bitrate results in a certain amount of data traffic per episode and is considered as input for the energy consumption and CO₂ 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 CO₂ emission? • How can an optimal operational point be derived (i.e., video bitrate) for the multi-criteria decision problem QoE vs. CO₂? • How much reduction in CO₂ emission can be achieved by a green user as compared to a high-quality user? • How much reduction in CO₂ 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 CO₂ emissions of green user behavior as compared to green networking?

A. Trade-off between QoE and CO₂ Emission

There is an obvious trade-off between the QoE and the CO₂ emission. Higher video bitrates lead to higher MOS values and user satisfaction – which is a nonlinear (logarithmic) relationship. At the same time, the CO₂ 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 CO₂ emissions are generated as compared to good QoE (MOS 4): the CO₂ emissions are more than doubled for any of the energy models and both user types.

The shaded areas indicate the amount of CO₂ 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 CO₂ emission compared with a green user. Similar behavior is observed for low bitrates.

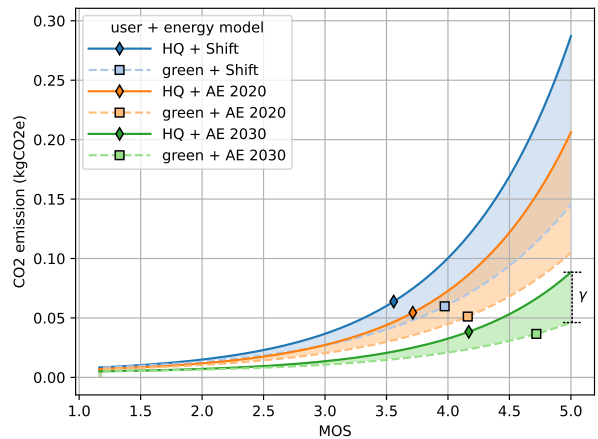


Fig. 2. Trade-off between QoE and CO₂ emission for the HQ user and the green user, portrayed across three different energy models. Optimal video bitrates according to Kleinrock’s power metric are identified, and resulting MOS and CO₂ emission is marked with a diamond (HQ user) or square (green user). The filled area presents the results for $\gamma \in [1, 2]$.

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–CO₂ trade-off. On the one hand, the QoE of users should be maximized, while on the other hand CO₂ 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–CO₂ curve. The power metric is the ratio of ‘goodness’ (i.e. QoE) divided by ‘badness’ (i.e. CO₂

emission). The optimization of power leads to a trade-off between maximizing ‘goodness’ (i.e., QoE) while minimizing ‘badness’ (i.e., CO₂ 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 CO_Nstraint 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., $y \cdot h(y - 3.5)$.

For the numerical results given in this article, we consider the MOS as being normalized to $[0, 1]$ as ‘goodness’ G and the CO₂ emission as ‘badness’ B . Thereby, despite the CO₂ emission from service usage, an additional constant offset of 0.05 kgCO₂e related to the production CO₂ 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 CO₂ emissions are much lower. The practical deployment scenarios to trade-off between MOS and CO₂ are discussed later.

C. CO₂ Emission for Optimal Video Bitrates

Next, we consider the CO₂ emissions as calculated for the optimal video bitrates from Figure 3. The CO₂ 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 CO₂ emissions, also for the identified operational video bitrates. The ratio of green energy leads to a significant reduction of the CO₂ 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 CO₂ 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

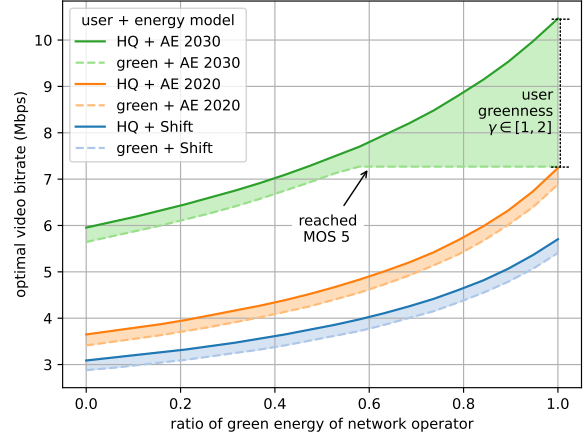


Fig. 3. Kleinrock’s approach is used to determine the optimal video bitrate. The Power metric is the ratio between MOS and CO₂ emissions. Its maximum identifies the suggested video bitrate.

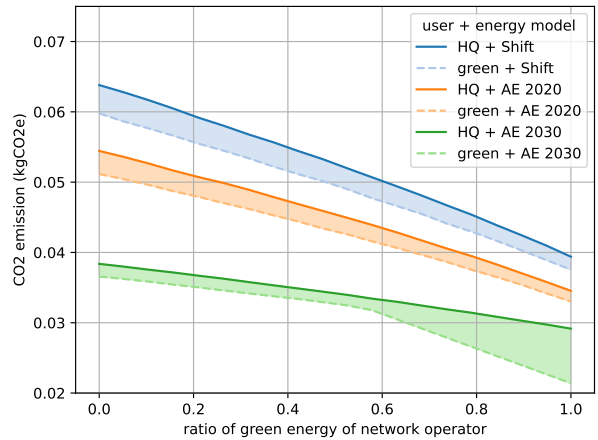


Fig. 4. The CO₂ emissions for the optimal video bitrates (see Figure 3) are calculated.

bitrates), or (b) the network becomes greener?

Figure 5 considers the relative difference of the CO₂ emissions in Figure 4 between the HQ user and the green user. In today’s Internet, this will save a significant amount of CO₂. However, the greener the network becomes, the green user does not result in an additional CO₂ 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 CO₂ emission reduction due to green energy. To this end, we calculate the CO₂ reduction of the HQ user for a ratio x of green energy relative to the CO₂ 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 CO₂ reduction. Especially, if 20%-30% green energy is used by the network operator, the relative CO₂ 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 CO₂ reduction, since the network is not generating significant CO₂ emissions anyway. Hence, it is nevertheless important a) to raise awareness of users on their CO₂ emissions and b) to empower users and provide them with the option of accessing Internet services in a green manner.

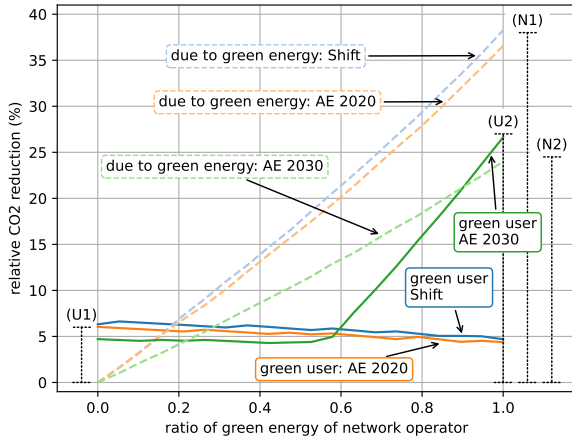


Fig. 5. Reduction of CO₂ emission due to green user (solid lines) and due to green energy in networking (dashed line). The following observations are marked in the figure: (U1) The relative CO₂ reduction of green users compared to HQ users is about 5% without green energy in today’s and future networks. (U2) In future networks (AE 2030), the relative CO₂ reduction due to green users is about 25%. (N1) In today’s networks (AE 2020, Shift), green energy may reduce about 35% of CO₂ emissions. (N2) In future networks (AE 2030), green energy may reduce about 25% of CO₂ emissions.

V. DISCUSSIONS AND IMPLICATIONS

Our results indicate that awareness of CO₂ emissions and empowerment of users to reduce CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂. 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 CO₂ 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.

As our numerical results indicated, the usage of green energy will have a large impact on CO₂ 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 CO₂/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 CO₂ emission (e.g., taking into account lifecycle assessment of devices) as well as energy consumption and the emerging CO₂ 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 CO₂ 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 (KVI) go beyond key performance indicators (KPI) 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’ (CO₂ emissions or energy consumption) can be seen as a concrete KVI. In practice, however, it is challenging to measure QoE and CO₂ 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 CO₂ 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 CO₂ 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 CO₂ values to meet sustainability goals from society and regulators.

The delivery of Internet multimedia services such as video streaming yields a trade-off between QoE and energy consumption as well as the resulting CO₂ 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 CO₂ 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 CO₂ 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/>.

- [8] A. S. G. Andrae and T. Edler, "On global electricity usage of communication technology: Trends to 2030," *Challenges*, vol. 6, no. 1, 2015.
- [9] L. Gibson, E. N. Wilman, and W. F. Laurance, "How green is 'green' energy?" *Trends in ecology & evolution*, vol. 32, no. 12, 2017.
- [10] L. Kleinrock, "Internet congestion control using the power metric: Keep the pipe just full, but no fuller," *Elsevier Ad hoc networks*, vol. 80, 2018.
- [11] I. Dabadie, M. Vautier, and E. Bertin, "'Your 6G or Your Life' How Can Another G Be Sustainable?" *Shaping Future 6G Networks: Needs, Impacts, and Technologies*, 2021.
- [12] A. C. Riekstin, B. B. Rodrigues, K. K. Nguyen, *et al.*, "A survey on metrics and measurement tools for sustainable distributed cloud networks," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 2, 2017.
- [13] V. Ziegler and S. Yrjola, "6g indicators of value and performance," in *2020 2nd 6G wireless summit (6G SUMMIT)*, IEEE, 2020.
- [14] A. Floris, A. Ahmad, and L. Atzori, "QoE-aware OTT-ISP collaboration in service management: Architecture and approaches," *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, vol. 14, no. 2s, 2018.
- [15] L. Skorin-Kapov, M. Varela, T. Hoßfeld, and K.-T. Chen, "A survey of emerging concepts and challenges for QoE management of multimedia services," *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, vol. 14, no. 2s, 2018.

VII. BIOGRAPHY SECTION



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