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**Institute for Future Energy Consumer
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The Electricity- and CO₂-Saving Potentials Offered by Regulation of European Video-Streaming Services

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Abstract

Massive increases in Internet data traffic over the last years have led to rapidly rising electricity demand and CO₂ emissions, giving rise to environmental externalities and network congestion costs. One particular concern is the rise in data traffic generated by video-streaming services. We analyze the electricity-saving potential related to video streaming in Europe from 2020 to 2030. To this end, three trend scenarios (Business-as-usual, Gray, and Green) are considered and modeled bottom-up, taking specific energy consumption (and trends) of data transmission networks, end-use devices, and data centers into account. Using these scenarios, we examine in more detail the approximate energy-saving impact that regulatory interventions and technical standards can have on the electricity consumption of end-users, network operators, and data centers. The model results reveal that regulatory intervention can have a significant impact on energy consumption and CO₂ emissions. As technical regulation carries the risk of stymieing innovation and dynamic efficiency, we propose economic regulation in terms of a mandatory transit fee as a long-term solution.

Keywords: Video streaming, Scenario analysis, Electricity-saving potential, Energy efficiency improvement, User behavior, Market failure, Internet traffic regulation

JEL Classification Nos.: D62, L82, L96, O33, O52, P48, Q47, Q48

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1 Introduction

Among other things, expert reports such as those from the WBGU (2019) at the national level or from the Intergovernmental Panel on Climate Change (IPCC) of the United Nations reflect concerns related to the negative effects of information and communication technologies (ICT)¹ and digitalization with regard to increasing electricity and energy consumption and the resulting carbon dioxide (CO₂) emissions. At the same time, however, the massive expansion of modern digital infrastructures (based on wireline fiber-optical transmission and wireless 4G(+) technologies) and corresponding energy efficiency gains on the supply side², as well as the widespread usage of new digital services and applications on the demand side, are also accompanied by various positive environmental effects.

Overall, the “megatrend digitalization”, which is based on ICT, offers considerable potential for both efficiency improvements and innovative applications, and for related reductions in energy consumption and CO₂ emissions. At the same time, it also holds potential for massive increases in electricity and energy consumption in the future. In the extreme case, rebound and obsolescence effects could fully offset (“backfire”) the positive effects. Most empirical studies examining the impact of ICT on CO₂ emissions suggest, however, a positive net effect.³ Therefore, if politicians aim to address the issue of ICT and energy consumption, they must take into utmost account the pronounced heterogeneity underlying the debate. Digitalization as a general phenomenon encompasses almost all areas of society and all economic sectors – with numerous positive and negative effects on the consumer (micro-), the industry (meso-), and the macroeconomic level of electricity consumption and corresponding CO₂ emissions (Briglauer et al., 2021).

Network expansion is an infrastructural necessity due to steadily increasing Internet traffic and the constantly increasing capacity requirements and emerging demand for high-quality

¹ The ICT sector includes the relevant telecommunication infrastructures (including broadband access and backbone networks) as well as ICT hardware and ICT services.

² Fiber-optic cable infrastructures are 85% more energy-efficient than copper-wire based legacy infrastructures, and 4G(+) can be 50 times more energy-efficient than 2G networks (World Bank, 2021).

³ See the tabular literature summary in Briglauer et al. (2021); whereas the overall net effect of ICT in terms of CO₂ emissions is still ambiguous, ICT as a “general-purpose technology” (Bresnahan, & Trajtenberg, 1995) induces substantial welfare gains via productivity increases, product innovations, and consumer surplus. This has been demonstrated by numerous empirical studies. Cardona et al. (2013) review the ICT-related literature, Bertschek et al. (2015) the broadband-infrastructure-related literature. In a more recent survey, Abrardi & Cambini (2019) review empirical studies related to new high-speed (fiber-based) broadband infrastructures.

Internet services. The main drivers of this rapid surge are, *inter alia*: streaming of videos with higher quality, video streaming for gaming, augmented reality (AR), artificial intelligence (AI) training, and autonomous vehicles with streaming cameras, holography, advanced commercials, and blockchain applications. Globally, the data traffic volume of 100 Gigabytes (GB) per day in 1992 had skyrocketed to 2000 GB per second by 2007. It was equivalent to 46,000 GB per second by 2017 and is estimated to reach 150'700 GB per second by 2022 (Cisco, 2020). This enormous rise in volume is not only attributed to the growth in the number of users, but also to the increase in a variety of (inter-) connected devices.

One area of concern relates to the massive increase in Internet data traffic from video-streaming services in recent years. At the household level, video-streaming has apparently become the “killer-app”, as it represents the application to which consumers attach the highest private value (Layton & Potgieter, 2021). The term video-streaming refers to the provision of video files which are hosted on physical servers that are separate from individual content users and their devices (TVs, Smartphones, PCs, Laptops, Tablets, etc.). Streaming refers to a delivery method where media content is provided continuously to the consumer, who does not have to download video files on their device points anymore (SHIFT, 2019). Online video-streaming services cover different usages, including in particular “video on demand” like films and series (e.g. Netflix, Disney+ or Amazon Prime), “Tube uses” (e.g. YouTube and pornographic sites), and social network uses (e.g. Facebook, Instagram, Twitter, or TikTok).⁴ Total video streaming and downloads are projected to grow from about 72% in 2017 to about 82% of annual global consumer Internet traffic by 2022 (CISCO, 2019).⁵ This development is related to the technology of online videos, which represents a very dense medium of information.⁶ Further increases in video-streaming traffic are expected when 4K/8K resolution displays become more widespread.

With hundreds of thousands of servers deployed in data centers from which the data can be accessed by end-users, there is also considerable electricity consumption, since these server capacities are in operation around the clock and every day (24/7). In addition to the electricity consumption for the actual computing power, a great amount of electricity is also required for cooling systems, i.e. air conditioning, re-cooling, etc. Videos are delivered to end-user devices

⁴ Livestreaming is a special case of streaming where media content is delivered in real-time – such as live television broadcasts, video conferencing (e.g. Skype, Zoom, Microsoft Teams, Cisco Webex) or social video-gaming communities (e.g. Twitch).

⁵ Other non-video data traffic segments are: websites, e-mail, instant messaging, company networks (VPNs, cloud computing), file sharing, and online gaming (Sandvine, 2019; Morley et al. 2018).

⁶ For instance, 10 hours of HD video consumption comprises a larger data volume than all English text articles on Wikipedia taken together (SHIFT, 2019).

from servers by using wireline and wireless network infrastructures. All these elements of usage and the provision of video-streaming services come along with substantial energy consumption and induce CO₂ emissions (SHIFT, 2019).

We examine in this paper (i) whether the massive growth in data traffic related to video-streaming services warrants regulatory interventions on the basis of externalities that cause market failure, (ii) trend predictions for electricity consumption and CO₂ emissions induced by video-streaming services in the absence of regulatory interventions, (iii) potential savings in electricity consumption and related CO₂ emissions in the case of regulatory interventions and technical standards, and finally (iv) which regulatory interventions should be implemented in terms of effectivity. The quantitative analysis involved in answering (ii) to (iv) focuses on core components of the ICT ecosystem (wireline and wireless access / core networks, endpoint devices, data centers) in selected major EU member states with trend predictions until the year 2030. Our paper sheds new light on the electricity-saving potentials of all system components related to video streaming, by undertaking a multi-scenario analysis that considers different regulatory approaches. To the best of our knowledge, at the European level no other studies have quantitatively addressed in such a comprehensive way the electricity-saving potentials related to video-streaming.

The remainder of this article is structured as follows. Section 2 reviews the related empirical literature. Section 3 outlines data-traffic-related negative externalities with respect to video-streaming services, and discusses in a more general manner basic forms of regulatory interventions for mitigating negative externalities. Section 4 describes the methodology and data applied as well as different scenarios used for trend predictions related to video-streaming services. Section 5 reports the results of our estimation of energy needs and describes electricity-saving potentials based on specific technical regulations including mandatory requirements (e.g. energy efficiency standards) and bans (e.g. no autoplay mechanisms). In Section 6, we discuss the results of our study and suggest possible approaches for tackling looming rises in energy consumption and resulting CO₂ emissions due to video streaming. Section 7 concludes with policy implications for the ongoing debate at the EU level on ICT and its climate impact.

2 Literature review

Massively increasing data traffic over the Internet has led to high electricity demand and corresponding CO₂ emissions. Dogan et al. (2017) empirically examine the impact of energy consumption using panel data from OECD countries and find a coefficient estimate of 0.93, i.e. an almost one-to-one relation between energy consumption and CO₂ emissions. Similarly, in a more recent study also using panel data from OECD countries, Briglauer et al. (2021) find

a coefficient estimate of 0.82. Most research predicts an exponential surge of data traffic for the coming years (Andrae, 2020). To name just a few, Weldon (2016) projected that electricity consumption of all connected devices would increase from 200 TWh in 2011 to 1100 TWh and 1400 TWh by 2019 and 2025, respectively. Hintemann (2020) argued that although different optimistic or pessimistic scenarios for data centers exist worldwide, phenomena such as video-streaming or the mining of cryptocurrency cause a noticeable increase in electricity consumption, which should be considered in all forecasting models.

The impact of data demand on energy consumption and environmental issues has been intensively disputed among researchers within industrial ecology, economics, engineering, and computing sciences. Shoukourian & Kranzlmüller (2020) show that despite higher electricity efficiency, the increase in density and performance of the Leibniz supercomputing center in Garching (Bavaria, Germany) is increasing the electricity consumption of the center. Andrae (2020) does not expect the total electricity consumption of the ICT sector to decrease or flatten out in the near future.

The electricity consumption of video-streaming can be divided into two elements: (i) the electricity consumption of the end-use devices on the side of the consumers, and (ii) the electricity consumption of data traffic on the side of the producers.⁷ The latter comprises the electricity needs of data transmission networks (including broadband access and backbone networks) and those of the data centers. Scientists have used several methods to model the overall electricity consumption of video streaming and have used various kinds of data sets and assumptions. The main challenges are a lack of information and data, a limited system boundary, over- or underestimation of the main parameters describing the system and its components, and a neglect of Moore's law.⁸ There exists a wide range of forecasts for each of the technical parameters in each section of the ICT ecosystem, creating a large set of projections for the future development. As a result, a strand of literature has used different scenarios for this analysis. For example, Koot & Wijnhoven (2021) present some projections for the electricity needs of data centers by using a system dynamics model. The impact of the COVID-19 pandemic is a prominent example that has markedly changed media consumption. Lemenager et al. (2021) show an increase in video-streaming hours during lockdowns among

⁷ Ignoring electricity consumption related to the production of videos themselves, which in the case of a large customer base might be quite negligible at least per subscriber.

⁸ Moore's law is a techno-economic model that states that the number of transistors in a densely integrated circuit doubles every two years. Interestingly, Moore's law still applies at the data center level (Shalf, 2020).

those affected. Therefore, this phenomenon should also be considered in the prediction of future energy consumption and CO₂ emissions related to video-streaming.

There are only few studies that explicitly examine the relationship between video-streaming and energy consumption. Schien et al. (2013) estimate the energy demand of digital media and conclude that total energy demand depends highly on the type of end-use device and the access network. Shehabi et al. (2014) recommend increasing the electricity efficiency of user devices and mandatory replacement of outdated components of the networks to restrict the energy consumption of video-streaming. Morley et al. (2018) find a relationship between online video-streaming, peak internet traffic, and national electricity demand. Suski et al. (2020) examine the role of user behavior (e.g. in terms of streaming duration, video resolution, and types of devices involved) on online video traffic and CO₂ emissions in Germany. Their study is the closest to our work, as it also describes how different regulatory regimes can affect the energy consumption and CO₂ emissions of video streaming.

Data centers are the backbone of the digitalized world (Masanet et al., 2020). They account for 1% of worldwide electricity consumption (IEA, 2017). Several studies have stated that their energy use has doubled in the last decade and can be expected to increase three or four times over the next decade (Belkhir & Elmeligi, 2018). Shehabi et al. (2016) state that the energy consumption of data centers in the USA has stabilized recently because of energy efficiency gains. However, Hintemann (2020) estimated that there was a 25% increase in energy consumption of data centers in Germany from 2010 to 2017. In contrast, Fuchs et al. (2020) investigated the impact of characteristics of volume servers⁹ of data centers on their energy use. The authors show that numerous algorithm-based methods exist that can be used to potentially decrease the electricity consumption of data centers – such as deep reinforcement learning (DRL), machine learning (ML), and artificial intelligence (AI).

Summarizing, most of the reviewed studies foresee an increasing trend with regard to the future energy consumption of data centers despite significant further energy efficiency gains anticipated. In our study, we aim at estimating the current and future energy consumption of video-streaming in Europe by taking the contributions of the data traffic and end-use devices explicitly into account. Contrary to previous empirical work, we analyze the impact of different trends in networks by using a scenario analysis of the energy consumption and CO₂ emissions that are induced by video-streaming services. In doing so, we take different regulatory approaches into account.

⁹ Volume servers are conventional computer servers. They are the primary source of electricity demand across all data center sizes and types (Fuchs et al., 2020).

3 Market externalities and regulatory approaches

Externalities are among the main reasons to justify any government market interventions on economic grounds. Positive or negative market externalities cause indirect effects, which impact on the consumption (utility) and production opportunities (costs) of other economic agents, but the market price of the product or service does not capture those externalities. To remedy market failure due to externalities, public policy makers or sector-specific regulators can impose taxes to overcome negative externalities or, alternatively, subsidies to internalize positive externalities. Regulators (or national governments) may also impose detailed technical regulations to mitigate capacity problems and to offset the effects of externalities. The extent of technical regulations will also depend on the scope of established industry self-regulations as well as on other mandatory sector-specific regulations. Socially optimal prices not only yield optimal capacity utilization in the short run but will also affect revenues and investment incentives of infrastructure operators in the long run.

In the following, we first describe in Sections 3.1 and 3.2 the two main sources of market failure related to video-streaming, before we discuss technical and economic regulations in Sections 3.3 and 3.4.

3.1 Environmental externalities

Today, global Internet data traffic is increasingly dominated by online video services. In the case of video-streaming, negative externalities are first related to high levels of energy consumption and corresponding CO₂ emissions, which make up the vast majority of greenhouse gas emissions and impose environmental costs to society. In order to limit global warming by limiting greenhouse gas emissions, the Paris Agreement, an international treaty on climate change that went into force in 2016, commits all the governments in the world to achieving a climate-neutral world by mid-century. Clearly, the main determinant of energy consumption in ICT networks is the volume of data traffic. The largest share of data traffic is generated by content providers (CPs) who control traffic flows over global networks, including data transmission networks. Note that the immediate impact of ICT is initially on the consumption of electricity, and only indirectly on CO₂ emissions. As shown in Section 2, the statistical relationship between energy consumption and CO₂ emissions is, however, very strong. Massive increases in data traffic thus cause, *ceteris paribus*, higher electricity and energy consumption and, ultimately, a corresponding increase in CO₂ emissions. The latter represent an environmental externality if data-traffic-generating agents do not internalize this source of social cost in their profit or utility maximization. If the externality is of much relevance in quantitative terms, a regulatory market intervention appears to be justified in the case where additional societal benefits outweigh the implementation costs of such remedial measures.

Past developments in traffic data, our trend predictions, and the related empirical literature discussed in Section 2 suggest that unless regulatory interventions are imposed, the “consumption effect” due to ever-increasing data traffic will most likely dominate opposing “greening” and “efficiency-enhancing” effects due to an increasing share of renewable energy sources and technological innovations.

3.2 Congestion costs

Another and perhaps more subtle source of negative externality induced by video-streaming services refers to potential network congestion costs. If ICT infrastructure components represent a scarce resource, infrastructure usage by an additional agent imposes a negative externality on all other agents. Under the best-effort Internet principle, where as many data as possible and as soon as possible are delivered, but where quality levels of data delivery cannot be guaranteed *ex ante* and network performance depends on the current network data traffic load,¹⁰ every agent can inject data packets into the Internet networks irrespective of network conditions or socio-economic benefits. This creates a negative congestion externality on all the other agents in the ICT ecosystem using the same congested network resources once over-usage at a certain stage in the value chain of the ICT ecosystem is reached. Even though often short-lived and transient states of congestion and resulting externality costs can be particularly high in periods of peak demands, i.e. when utilization rates are highest and network resources most scarce. Whereas data traffic is generated by CPs, telecommunications companies (telcos) provide the network infrastructure to transport data connecting end-users / a destination host with CPs. The negative congestion externality manifests itself in impaired Quality of Service (QoS) levels in terms of higher delays, jitter, packet loss, and lower bandwidth levels, which may ultimately also lower the Quality of Experience (QoE) for end-users (Stocker, 2020).¹¹ Given the continuing increase of data traffic stemming from various kinds of video-streaming services, any additional provision of video services under best-efforts principles imposes a negative externality on all other digital services and applications in the presence of capacity constraints along the ICT supply / value chain. These are temporary effects as network operators invest in capacity upgrades to transport increasing volumes of traffic. The extent of negative congestion externalities from video-streaming services will depend on the economic value of these services in comparison

¹⁰ Accordingly, each data packet has the same expectation of delivery and quality while it transits via networks to a certain destination host (Carpenter & Nichols, 2002).

¹¹ Note that these concepts can differ, as QoS describes the quality of packet delivery from a technological perspective, whereas QoE describes the quality of an application or service as perceived by an end-user (Stocker & Whalley, 2018).

with all other digital services in terms of the respective impacts on consumer surplus, productivity, labor, and other GDP-related effects. Note that there might be a trade-off between high private value and resource-intensive services with services exhibiting high social value and more modest demands for network resources (Layton & Potgieter, 2021). Note also that this assessment will result in different outcomes in times of global economic crises with major shutdown policies, as experienced in the COVID-19 pandemic. During this crisis, society has become even more dependent on a good and reliable access to high-quality broadband infrastructures, and some digital services appeared to be particularly important for mitigating the consequences of economic downturns (e.g. e-health, e-learning and e-teaching, teleworking based on video-conferencing, VPN access, or cloud-computing).

3.3 Economic regulation

In order to internalize negative externalities, economists often refer to market-based pricing mechanisms, where externalities are internalized by implementing social marginal costs e.g. of “congestion” or “pollution” in individual profit-maximizing behavior by charging a Pigouvian tax (Pigou, 1920) per unit of output. This tax reflects the difference between private and social marginal costs at socially optimal output levels (Stocker, 2020). A Pigouvian tax might be imposed on the demand side (end-users) or the supply side (CPs). Tudón (2019) argues that whereas a small Pigouvian tax on the demand side decreases consumer surplus, it does not when imposed on the supply side. Using data from Twitch, the author finds that cross-side network effects are larger for CPs than for end-users. Therefore, the platform’s size decreases less when CPs rather than end-users are taxed. Also, end-users are typically not aware of the network congestion costs or electricity consumption related to specific applications and their delivery via the relevant ICT supply / value chains. Finally, as many CPs offer flat-fee pricing modes to end-users, the latter will often result in high usage intensities and no incentives to reduce consumption of content as externality costs are not captured (Layton & Potgieter, 2021).

In a sector-specific context, a regulatory authority might set a “transit fee” that is imposed on a certain unit of quantity of data traffic, which ideally captures both types of externalities considered (environmental costs due to CO₂ emissions and network congestion costs).¹² An economically efficient transit fee would not only reflect total social costs; it also reflects volatile demand patterns and, given short-term fixed transport capacities, yields an optimal allocation

¹² A similar policy is suggested in a recent paper by Layton and Potgieter (2021) who examine the business case of rural broadband providers in the U.S. The authors propose, *inter alia*, that regulators introduce a “compensation fee” in case commercial negotiations between telcos and CPs fail.

of network resources.¹³ Transit fees should also incentivize CPs to optimize the QoE for their consumers, taking into account the social costs of relevant data traffic and thus to deliver their content to end-users in an economically efficient manner. This might involve the use of technologies to compress their content and to dynamically adapt their sending rates according to current utilization levels of network resources.

Market failures as described in Sections 3.1 and 3.2 resemble the so-called “free rider” problem, which occurs whenever beneficiaries (CPs) from resources (data transmission network infrastructures) do not have to pay for them. In fact, leading providers of different categories of video-streaming services have by and large succeeded to evade participation in the recovery of costs for data transmission infrastructures in the past (Layton & Potgieter, 2021). Free-riding phenomena are a social problem in general, because the service under consideration may be under-produced (not enough incentives to invest in broadband infrastructure), overused (network congestion), or degraded (impaired levels of QoE), if the total social costs of usage are not appropriately taken into account.

Although economic regulation in terms of introducing a mandatory transit fee is the most efficient way of internalizing market failures also in the context of video-streaming data traffic, it faces the challenge of institutional rigidities and complex implementation. In particular, as the popularity of video-streaming services represents a “killer-app” phenomenon that likewise impacts all developed countries, it would have to be regulated at a supra-national level. Accordingly, the European regulatory framework would have to be adjusted to allow for such a regulatory instrument (price regulation). This most likely involves time-consuming debates and procedures both at the EU and the member state levels.

Our focus in this paper is mainly on easy-to-grasp and presumably easier to implement technical regulations as a rudimentary first attempt to more timely address market failure issues, and to estimate the climate benefits of regulating data traffic. We leave a more detailed and rigorous analysis of economic price regulations for future research.

3.4 Technical regulation

Next to economic price regulation, technical regulation provides an alternative remedial measure to internalize any negative externalities related to video-streaming services. These regulations are at the center of our analysis in Sections 4 and 5 below. They include prohibitions such as “no autoplay mechanisms”, which are still used by some streaming providers, or requirements such as “data compression” and related “encoding techniques”.

¹³ For a comprehensive analysis of incentive-compatible and economically efficient price and quality differentiations that yield optimal capacity allocation in all-IP networks see Stocker (2020).

Such technical efficiency-enhancing regulations would reduce network loads and utilization levels, and thus end-to-end QoS levels can also be improved (Stocker, 2020). Video-streaming providers already adhere to these practices to some degree under self-regulations subject to profit-maximizing behavior. But as such, industry-wide self-regulations typically do not consider negative externalities exerted on other digital services and applications or CO₂ emissions and might also be subject to coordination failure. In the context of (company-level) voluntary self-regulation, some of the major CPs – like Apple, Google, and Microsoft – have also switched already partially or even entirely renewable energy sources, aiming to offset their CO₂ emissions (World Bank, 2021).¹⁴ Hedging against volatile energy prices and improving brand reputation are other drivers of corporate renewable energy procurement or self-generation. However, this does not guarantee that data centers will always be powered by renewable energy sources, because of the intermittency of wind and solar power. Thus, it is important for CPs to take the location of data centers (DC) and the temporal and spatial availability of renewable electricity into account as well (IEA, 2020). Furthermore, the energy mix involved in video-streaming is only under partial control of CPs within the ICT ecosystem. For instance, there is no control with respect to end-user devices or data transmission networks, or in the production of consumer-generated content.

Public policies to fund the deployment of high-speed broadband capacities would mitigate network congestion problems. Whereas overcapacities in network infrastructure are essential and can be seen as a necessary condition for high QoS and QoE levels, they neither constitute a sufficient condition (Stocker & Whalley, 2018) nor do they imply efficient resource allocation.

Summarizing, the role and relevance of governmental interventions in terms of market price regulations à la Pigou or in terms of technical regulations depends on (i) the expected development of data traffic generated by video-streaming in the case where such regulations are not imposed, (ii) the extent and scope of voluntary industry self-regulation, (iii) the impact of other related public policies or sector-specific regulations, and (iv) the actual extent of negative externalities with respect to CO₂ emissions and impaired QoS of other digital services and applications in the case of network congestion.

¹⁴ Similarly, Netflix reduced its average streaming quality in Europe to avoid straining the ICT ecosystem during the COVID-19 pandemic (information available online: <https://www.weforum.org/agenda/2020/03/netflix-is-reducing-the-quality-of-its-streams-in-europe-to-avoid-straining-the-internet-during-the-coronavirus-outbreak/>); whereas this can be seen as a dynamic and market-driven (self-regulated) data traffic adjustment mechanism, it also underlines the potential for network congestion.

4 Methodology and scenario building

In answering our research questions, we first estimate the current and expected future electricity consumption of video-streaming in Europe in order to analyze the technical energy-saving potentials in access network, core network, data centers, and end-use devices. To this end, the bottom-up methodology, which has been used for the calculation of electricity consumption, is presented in Subsection 4.1. Subsection 4.2 then describes the data and the assumptions used. In projecting the future energy consumption and CO₂ emissions of video-streaming in Europe, we consider different trends in different scenarios, and several descriptors as outlined in Subsection 4.3.

4.1 Methodology

Figure 1 illustrates the relevant boundaries and the role of each component within the ICT ecosystem. As can be seen, all relevant components, including end-use devices, data transmission networks and data centers generate data traffic (solid arrows) and consume electricity (dashed arrows).

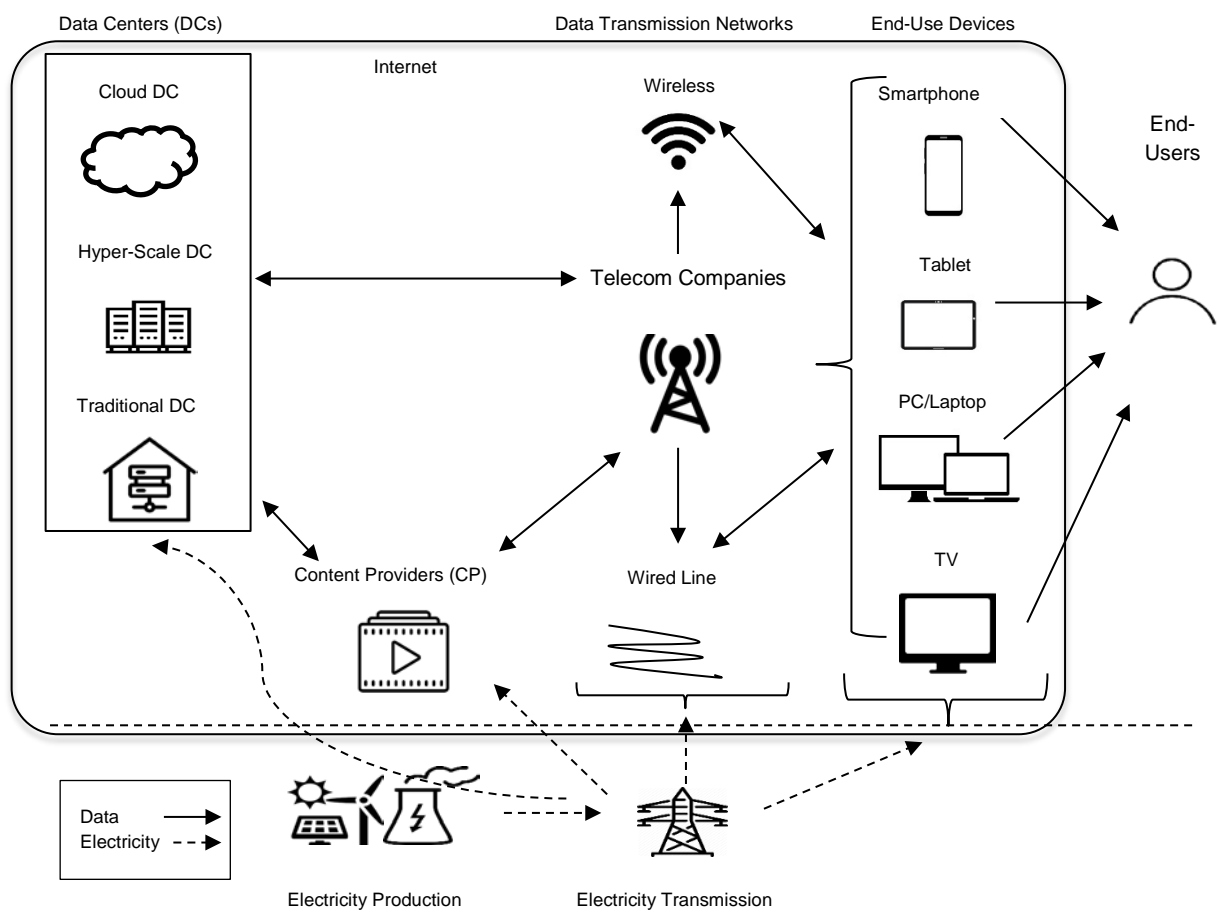


Fig. 1. Illustration of relevant ICT ecosystem components considered for online video-streaming

In the first pillar, subscribers contribute to electricity consumption by using their devices. In the second pillar, the connected devices to the Internet (via wireless or wired line) constitute the second part of electricity consumption, in which telecommunication companies convey the signals of the users to the content providers, and vice versa. Based on the business models of the content providers, the requested data are sent from the last pillar (data centers) to the users.

For the modeling of the energy-consuming processes involved in video-streaming, we make use of a simplified approach proposed by Suski et al. (2020). We consider end-use devices and data traffic in terms of ICT infrastructure such as data transmission networks and data centers. The electricity consumption of streaming on devices over a week can be approximated by eq. (1).

$$Q = Q_{device} + Q_{data\ traffic} \quad (1)$$

$$= \sum_{i=1}^4 (t_i * (P_i + R_i * \rho)),$$

where Q stands for electricity consumption (kWh), i represents the type of device, t_i depicts the streaming hour over a week for device i , P_i stands for power of device (W), R_i for data traffic for resolution of device type i (GB/h), and ρ shows the electricity intensity¹⁵ of data traffic (kWh/GB). Multiplying the electricity consumption by the CO₂ intensity of electricity leads to the total CO₂ emission of the video-streaming of devices (eq. (2)). For simplicity reasons, we use the average CO₂ emission intensity in the power grid of Europe (2021 projected to be around 240 g CO_{2eq}/kWh; cf. www.eea.europa.eu/data-and-maps), which may vary in different countries:

$$CO_2 = CO_{2device} + CO_{2data\ traffic} \quad (2)$$

$$= \sum_{i=1}^4 (t_i * (P_i * \gamma + R_i * \rho * \gamma)),$$

where γ stands for the CO₂ intensity of electricity in Europe.¹⁶

¹⁵ The energy intensity is calculated as units of energy (kWh) per unit of data traffic (GB).

¹⁶ The sample average is based on data from [statista.com](https://www.statista.com), covering 28 European countries (excl. Switzerland and Norway but including the UK).

4.2 Data

For the analysis of the proposed scenarios, we use data from different sources, including technical data of users' devices, streaming hours of users, ICT infrastructure, and CO₂ emission intensity. In this section, the data used for the model are briefly presented. Further details on the data can be obtained from the authors upon request.

4.2.1 End-user devices for video-streaming

People use several devices for their video-streaming and various factors influence the resolution and corresponding energy consumption of these devices. The four most common resolutions are: low ($\leq 360p$), middle (480p), high density (HD) (720p), and ultra-HD (1080p). However, we have considered a constant, i.e. time-invariant, resolution for each device used because according to Suski et al. (2020), less than 15% of the users tend to change the default resolution of their devices. The default standard resolution of the devices is reported in Table 1. For the calculation of the energy consumption of each device, we need information on the utilization rate of the devices as well (Table 1). For this purpose, we employ user behavior data on video streaming that is based on a recently conducted survey in Germany (Suski et al., 2020).

Table 1: Resolution and bitrate of included devices

Device	Standard resolution [p]	Bitrate [GB/h]	Load [W]	Weekly usage [h]	Source
Smartphone	360	0.3	6	3.76	Suski et al. (2020)
Tablet	480	0.45	7	0.97	Suski et al. (2020)
Laptop/PC	720	1.2	32	4.92	Suski et al. (2020)
Smart TV	1080	1.8	200	2.49	Suski et al. (2020)

Note: p = pixels per inch

4.2.2 Data traffic

In order to model the energy consumption of ICT infrastructure, we use energy intensity related to data traffic via wireless and fixed line data transmission networks and data processing in data centers. Details are presented in Table 2.

Table 2: ICT infrastructure (comprising access network, and data center)

	Electricity intensity of data transmission [kWh/GB] (2020)	Source
Access Network	0.079	Andrae (2020), Shien et al. (2014), Arcep (2019)
Core Network	0.006	Andrae (2020) , Shien et al. (2014), Arcep (2019)
Data center	0.015	Andrae (2020)

4.3 Scenario description

Freitag et al. (2020) show that in recent studies assumptions regarding energy efficiency improvements, ICT demand, rebound effects in ICT, and ICT's role in climate change vary considerably. To predict the expected electricity consumption and CO₂ emission levels attributable to video-streaming, one needs to make sure that we show two (arbitrarily chosen) alternative scenarios to the trend/baseline scenario in order to show how the relative shares and trends can be expected to change. Hence, we decided to investigate three different scenarios (business-as-usual / BAU, Gray, and Green), which can be characterized as follows:

- *BAU scenario*: In this baseline scenario, we assume a continuation of the recent trends regarding the efficiency of the end-use devices, and the energy intensity of components of the data traffic systems and end-use devices used for video-streaming.
- *Gray scenario*: In this pessimistic scenario, a constant CO₂ emission trend, rather low energy efficiency improvements, and higher consumption than in the BAU scenario are assumed.
- *Green scenario*: This very optimistic scenario shows a greener future with higher energy efficiency levels, lower emission rates, and more energy-efficient consumer behavior. The decreasing trend in CO₂ emissions also reflects an increasing share of renewable energies in this scenario.

The three scenarios considered are built based on seven descriptors in total, including the number of subscribers / users, electricity efficiency (or intensity), share of renewables, streaming duration, and resolution choice, among others. Table 4 gives an overview of all of them and provides some information about each descriptor. The number of users represents the number of people who consume video streaming in Europe (Statista, 2020). Although this descriptor undergoes an increasing pattern in all scenarios (a rise from 159 million in 2020 to

176 million in 2030), we assume a higher increasing rate in the worst-case scenario (259 million in 2030). Analogously, the electricity efficiency of the devices will also rise in all scenarios. The third descriptor is the CO₂ emission intensity; this descriptor has been used to show how the trend assumed for CO₂ emission factor will change in the future for the different scenarios. The fourth descriptor reflects the electricity intensity of networks and the fifth represents data centers. As most of the studies predict a decreasing trend for the electricity intensity of network and data centers, a decreasing trend has been considered in the Green scenario. The duration of streaming can affect the energy consumption and CO₂ emissions accordingly (sixth descriptor). Hence a constant, and an increasing pattern for it have been considered in the Green scenario, and the BAU/Gray scenario, respectively. The seventh descriptor is the quality of video streaming in terms of the resolution of the streaming, which can noticeably impact the energy consumption.

Table 3: Descriptors and parametrization used in video streaming scenario investigated

Descriptor	BAU	Gray	Green
Number of subscribers	Rather low (1% p.a.)	Increasing (5% p.a.)	Rather low (1% p.a.)
Electricity efficiency of end-use devices	Average improvement (5% p.a.)	Low improvement (2% p.a.)	High improvement (10% p.a.)
CO ₂ emission intensity	Decreasing (1% p.a.)	Constant	Decreasing (2% p.a.)
Electricity intensity of data networks	Decreasing (2% p.a.)	Constant	Decreasing (5% p.a.)
Electricity intensity of data centers	Decreasing (2% p.a.)	Constant	Decreasing (5% p.a.)
Streaming duration	Higher (1% p.a.)	Higher (2% p.a.)	Constant
Resolution choices	Average improvement (15% p.a.)	Higher improvement (25% p.a.)	Lower improvement (10% p.a.)

5 Results

In the following, we provide an estimate of the current and future electricity consumption of video-streaming. In Subsection 5.1, the energy consumption, the CO₂ emissions, and the relative shares of end-use devices, and the data traffic in weekly electricity consumption are presented. In Subsection 5.2, first the impact of regulatory intervention in terms of imposing

different technical regulations is presented. Then, the impacts of the access network and core network on energy consumption of video streaming are analyzed. Finally, the important role of data centers in the energy consumption of video-streaming is scrutinized by using our three trend scenarios.

5.1 Estimation of energy demand trends

The energy consumption of video-streaming shows a variety of results in different scenarios. As expected, people consume more energy in the Gray scenario when, on the one hand, the number of users and streaming hours are assumed to increase and, on the other hand, energy efficiency increase less than in the other two scenarios. As a result, from 2025 onwards, energy consumption increases substantially (four times) compared to that of the other scenarios. However, as can be seen in Figure 2, a 10% electricity efficiency improvement of end-use devices and a 5% electricity efficiency improvement of data traffic does not necessarily lead to lower energy consumption per subscriber and week of streaming. This accentuates the important role of energy efficiency improvements of the streaming devices used for reducing total energy consumption. In contrast, the Green scenarios show a rather constant pattern in both total energy consumption and energy consumption per subscriber and week. Overall, this scenario-based analysis reveals that reducing streaming hours of users and energy efficiency improvement can lead to a high electricity-saving potential. The electricity-saving potential of the Green scenario is 21.2 TWh compared to the BAU scenario. This is equivalent, for instance, to the yearly electricity generation of three mid-sized coal power plant (~900 MW) with an availability factor of 90% (~8000 full-load hours).

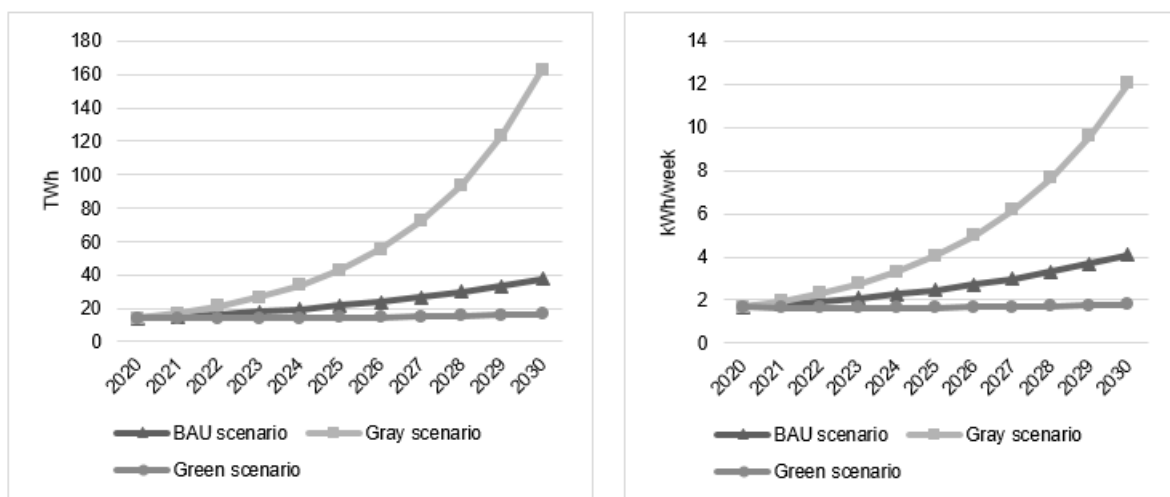


Fig. 2. (a) Electricity consumption for video-streaming in Europe [TWh]; (b) Average electricity consumption per subscriber and week [kWh/week], 2020–2030

The environmental assessment of video-streaming shows different trends in the different scenarios (Figure 3). The trends of these scenarios bear a close resemblance to the energy consumption trends. However, the Green scenario shows a nonlinear negative trend. The reason behind this trajectory is rooted in the declining trend of CO₂ emission intensity in this scenario (-2% p.a.). The overall unitary CO₂ emissions from the video-streaming of one subscriber is 0.36 kg CO₂-eq per week. Considering this as an average streaming behavior, it would add up to 18.7 kg CO₂-eq per year. In 2030, this number is expected to be 0.41, 0.8, and 0.31 kg of CO₂-eq per week for the BAU, Gray, and the Green scenario, respectively. A comparison between Figures 2 and 3 reveals that while electricity consumption rises 8-fold within a decade in the Gray scenario, CO₂ emissions only rise by a factor of about 2.5.

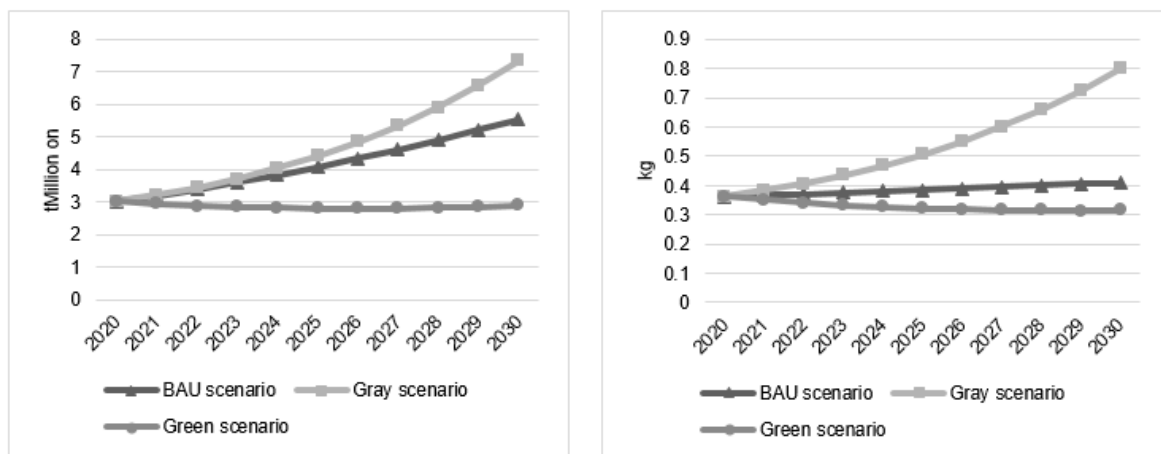


Fig. 3. (a) CO₂ emissions of video streaming in Europe; (b) Average CO₂ emissions of video streaming per subscriber and week in Europe, 2020–2030, by scenario

As mentioned in the introduction, two main components of video-streaming are the end-user devices and data traffic. Figure 4 depicts the relative shares of these two components in terms of weekly electricity consumption in all three scenarios from 2020 to 2030. All scenarios demonstrate that data traffic has a dominant share. This finding is in line with previous studies (e.g. IEA, 2020). Furthermore, the share of end-use devices in electricity consumption decreases in all scenarios, even in the Gray scenario. This highlights that policy-makers and industry experts should be more cautious regarding the energy consumption in the data traffic sector. In the Green scenario, weekly electricity consumption per subscriber reaches 0.23 kWh/week and 1.5 kWh/week for devices and data traffic, respectively. This confirms that energy efficiency improvements in the data traffic segment (network and data center), as, for example, increasing the efficiency by setting reasonable prices for data traffic in the backbone and incentives for data economy on the part of the CPs, can decrease the expected weekly energy consumption markedly.

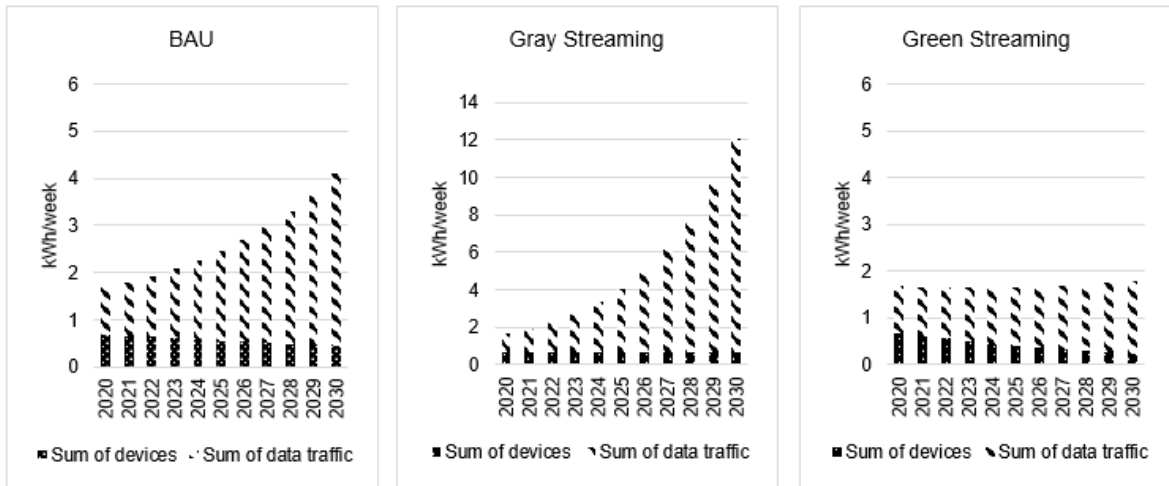


Fig. 4. Relative shares of end-use devices and data traffic in weekly electricity consumption, 2020–2030, by scenario

Figure 5 shows that efficiency gains in all components (i.e. end-use devices, network, and data center) cannot compensate the impact of the increasing number of subscribers and streaming hours of users on the absolute electricity consumption. On the one hand, although Moore's Law has slowed down since 2012, many scientists, including Masanet et al. (2020), predict further efficiency improvements in data centers. On the other hand, other studies, such as Andre et al. (2020) or Belkhir et al. (2018), conclude that energy efficiency improvements might reach their limits. The comparison of Figure 5a and 5b illustrates that energy consumption is approximately 4 TWh lower when efficiency improvements are included, compared to the situation where no efficiency improvement is assumed.

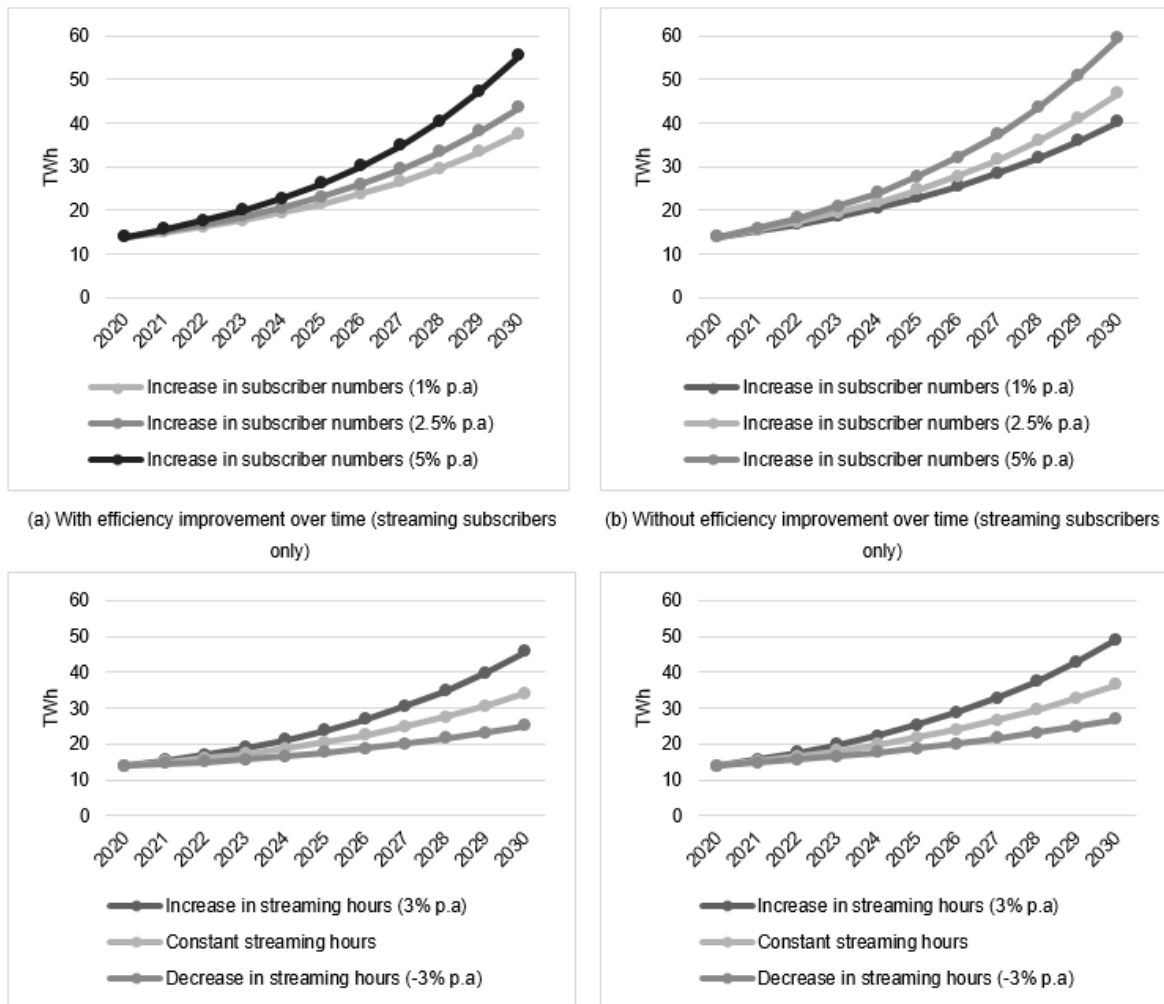


Fig. 5. Comparison between the impact of subscriber numbers and streaming hours on total electricity consumption for video streaming in Europe, with and without energy efficiency increases, 2020–2030

5.2 Impact of technical regulations on energy savings

In this subsection, we assess the impact of technical regulations on the electricity-saving potentials based on (i) (default) resolution, (ii) network adjustments, and (iii) data center components.

5.2.1 Default resolution

Figure 6 shows the development of energy consumption in different scenarios for two cases: streaming with default resolution of all devices, and streaming with minimum resolution. As can be seen, reducing the resolution default to the minimum resolution has a positive impact in the short term in both the BAU and the Green scenario. Therefore, such regulation seems better suited as a short-term policy measure.

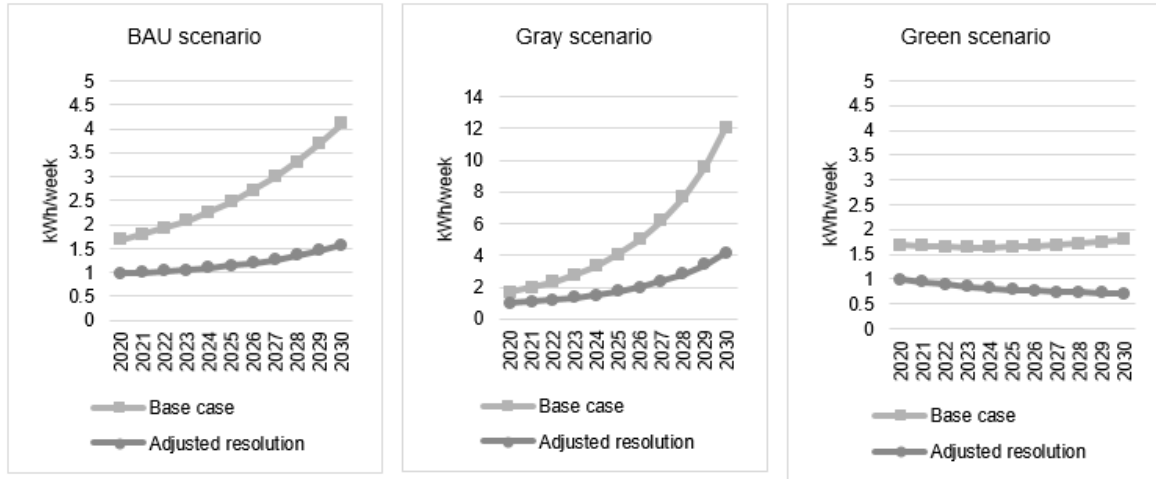


Fig. 6. Average electricity-saving potential per week of reducing the resolution of all end-use devices to 360p, 2020–2030, by scenario

Regulators or CPs can take up various strategies to reduce the energy consumption of video-streaming. Figure 7 illustrates the impact of four different strategies on the energy consumption per subscriber and week. It shows how the resolution setting can change the energy consumption of video-streaming. As expected, it shows that a 360p resolution for all end-use devices can lead to the lowest electricity consumption of one user per week compared to the others. Interestingly, as many people enjoy video streaming with a PC/laptop, which has almost four times the bitrate of smartphones, issuing such regulations for one of the device types – like PC/laptop – can also reduce the electricity consumption noticeably. The comparison of the other strategies shows that the strategy which encourages streaming with default resolution on smartphones (360p) can also noticeably decrease electricity consumption per subscriber and week. Furthermore, in 2030 the order of the strategies do not change substantially. However, all of them undergo a noticeable rise, which is related to increase in data volume. Since in the BAU scenario, constant annual/weekly streaming hours over the years are assumed, we incorporated these strategies into this scenario as well.

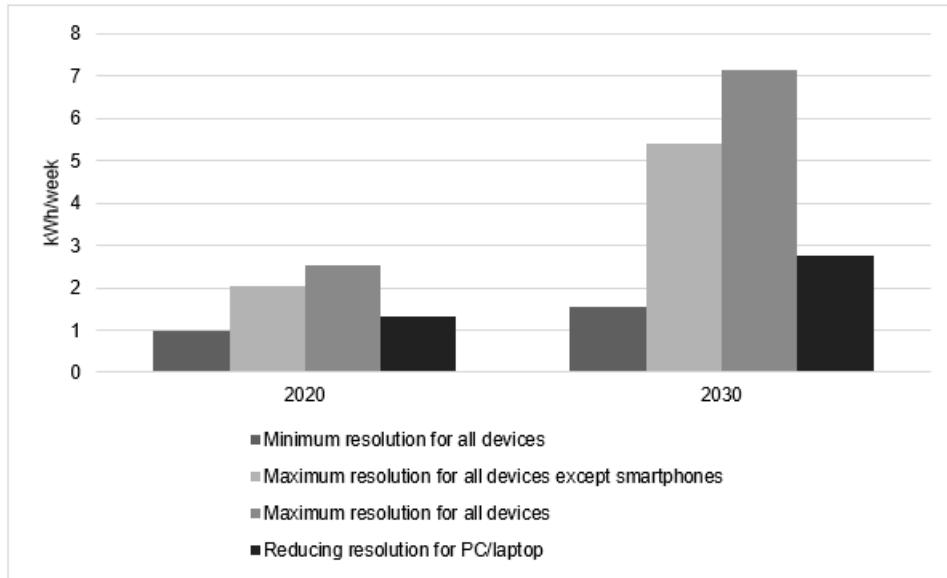


Fig. 7. Average electricity-saving potential per subscriber and week through the adjustment of the default resolution, by end-use device groups, 2020 versus 2030

5.2.2 Network adjustment

As the penetration of wireless technologies would increase noticeably compared to the fixed line network, we take into account different patterns for a share of 3G/4G and 5G in order to address the expected impact of wireless technology on the energy consumption of video-streaming. The data on the wireless technologies are based on STL Partners (2018).

As shown in Figure 8, using more energy-efficient technologies in the access network and core network can reduce energy consumption significantly. In order to study the impact of an efficiency improvement of networks on electricity consumption, we use different shares of wireless technologies in each scenario. The introduction of mm-wave technologies in 2023 can enlarge the gap between the Gray and the Green scenario. As Figure 8 pinpoints, energy-efficient wireless technologies can reduce electricity consumption markedly in the long term. However, as can be seen, energy efficiency gains (due to autonomous technical change) in wireless technologies alone are insufficient and highlight the significance of economic regulation in networks to reduce the electricity consumption. Furthermore, the differences in the electricity consumption of one user per week have a direct relationship with the climate friendliness of the scenarios, which states that the optimal mix of wireless technologies can be more helpful in the Green scenario. Interestingly, it can be deduced that both consumers (by streaming with lower resolution) and operators (by investing in new, energy efficient wireless technologies) can control increase of energy consumption.

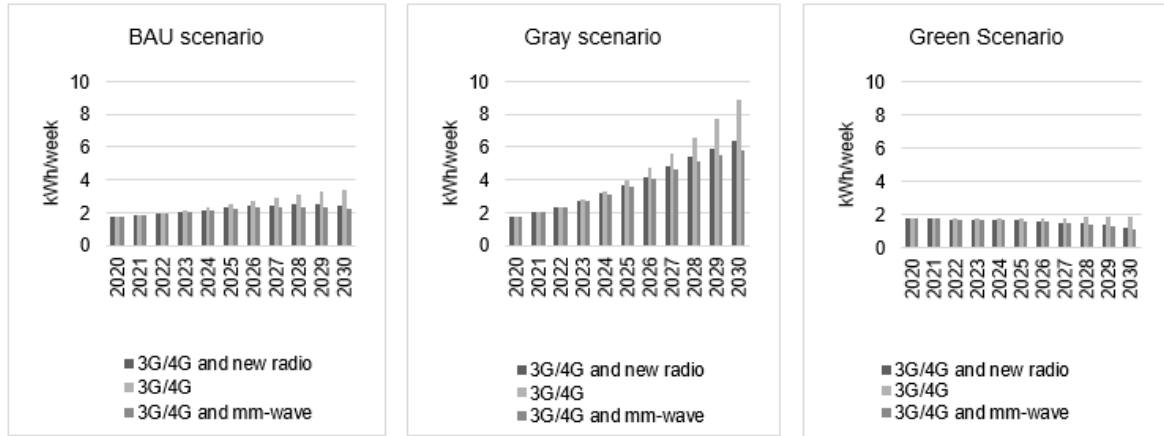


Fig. 8. Energy consumption of different wireless technology combinations, 2020–2030, by scenario

5.2.3 Data center components

Data centers (DC) can be categorized into three main groups: traditional, cloud, and next generation (incl. hyper-scale DCs). According to the International Energy Agency (IEA, 2020), data centers consume almost 220 TWh globally, and thus approximately 17% more than wide area networks. Cloud has the largest proportion after traditional data centers. In this experiment, we use a different mix of data center technologies in different scenarios in order to evaluate the impact of the data centers' mix on electricity consumption of one user per week among the three scenarios. Figure 9 shows that shifting to the system with a higher share of energy-efficient data centers can hardly lead to a higher energy- (and CO₂-) saving potential. The reason behind this result is that the impacts of the energy intensity of different data center types are approximately similar. However, apart from the Gray scenario, the energy-saving potential is higher in the following years. Hence, energy-efficient data centers as well as networks would help to decrease energy consumption in the longer term in the Green scenario. In other words, both data center and network operators need long investment horizons in order to increase the energy efficiency of their systems.

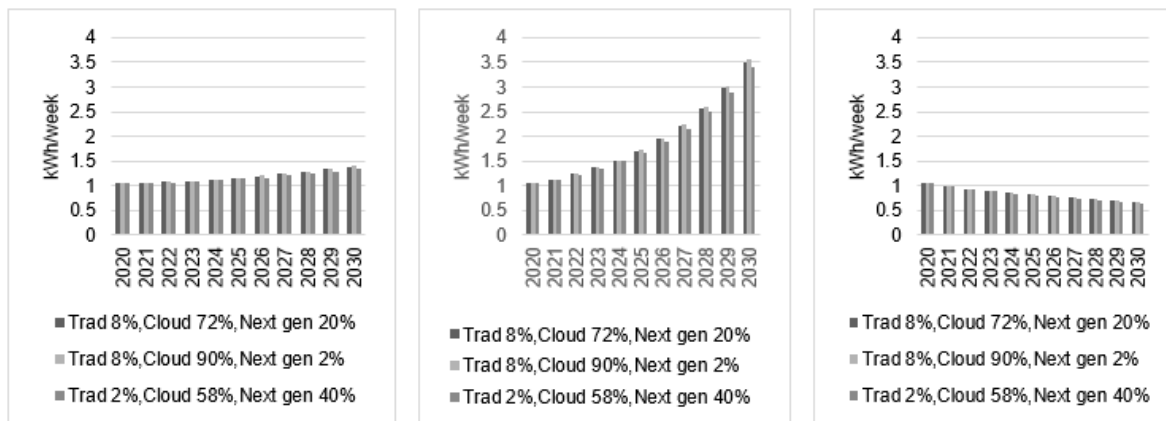


Fig. 9. Average weekly electricity consumption of data centers (proportion used for video-streaming), 2020–2030, by scenario

5.3 Combined scenarios

Previous sections cover the impact of technical improvements in each part of the video-streaming process. Since the rapid technical change in networks and data centers are happening in parallel, we analyze the combined effect of them in order to predict future electricity consumption more realistically. Regarding wireless technologies in the access network, we did not consider any share for 5G in 2020, but in 2030 it accounts for 68%, 0%, and 100% of the wireless technologies in the BAU, Gray, and Green scenarios, respectively. Although the new generation of data centers still have had a very low share in recent years, it is projected to represent 20% of the segment “data” by 2030. This is because of the efficiencies obtained from the increased use of the new technologies. We use this assumption for the BAU scenario. This share remains at 2% over the years in the Gray scenario; we assume that it can transfer a higher share of data by 2030 in the Green scenario (30%). This additional efficiency improvement is projected due to uncertainties about the extent to which these intelligent and energy-efficient technologies will be implemented. Traditional data centers are assumed to account for 8% of all data centers in the scenarios BAU and Gray. However, their share reduces to 2% in 2030 in the Green scenario. Cloud shares will also decrease, as the significance of next generation data centers is expected to rise in the future, although its share is assumed to remain constant (just like the other shares in the Gray scenario).

Figure 10 represents the electricity consumption of one subscriber per week from a holistic perspective. These scenarios encompass the development of both networks and data centers from the previous sections. Therefore, the energy consumption of the subscriber is shown from a more realistic perspective. As can be seen, compared to previous sections, the Green scenario witnesses a declining trend, which stems from a reduction in energy intensity of both networks and data centers. However, the gap between the BAU and the Green scenario

widens in further years. This emphasizes how the simultaneous impact of networks and data centers can speed up the reduction of the per unit energy consumption. As is shown, new technologies in data traffic cannot reduce electricity consumption when data volume rise noticeably (Gray scenario).

Table 4: Assumed data center and network technology shares, 2020 and 2030, by scenario

Scenario	BAU		Gray		Green	
	2020	2030	2020	2030	2020	2030
Share of 3G/4G	100%	32%	100%	100%	100%	0%
Share of 5G	0%	68%	0%	0%	0%	100%
Wireless technology	3G/4G and new radio		3G/4G		3G/4G and mm-wave	
DC-traditional share [%]	8	8	8	8	8	2
DC-cloud share [%]	90	72	90	90	90	58
DC-next generation share [%]	2	20	2	2	2	40

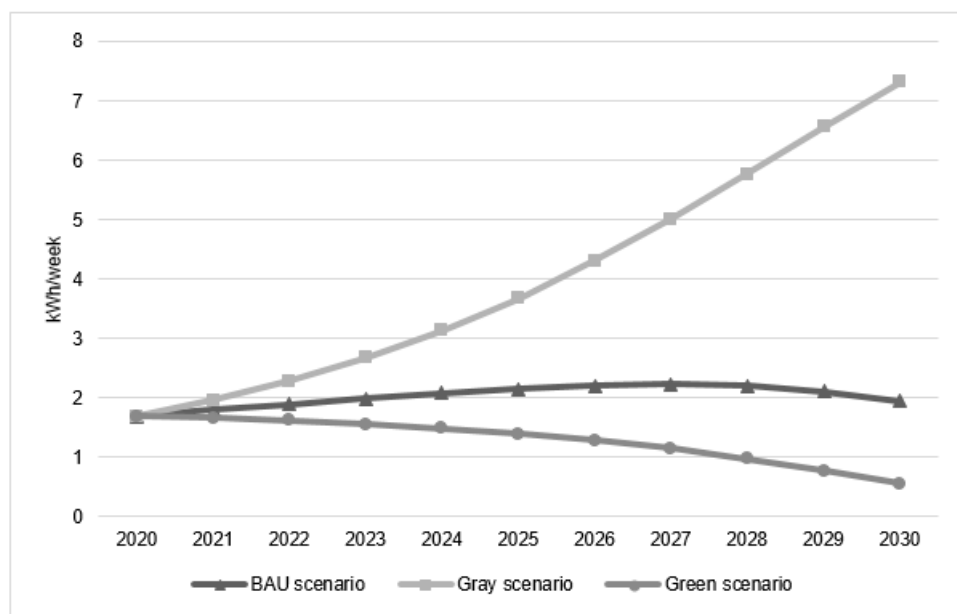


Fig. 10. Estimated total weekly average electricity consumption due to video streaming in Europe, 2020–2030, per subscriber and week, by scenario

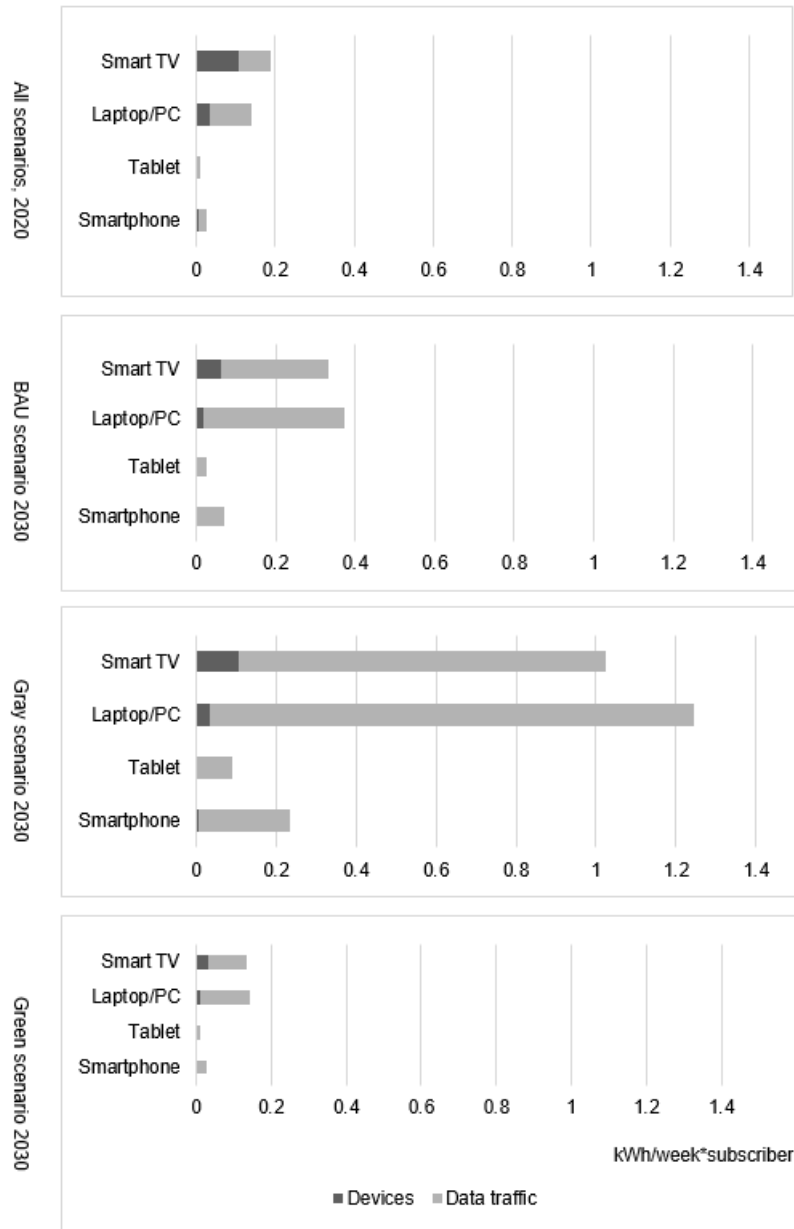


Fig. 11. Relative contributions of the different types of end-use devices vs. contribution of data traffic in terms of average weekly electricity consumption per subscriber, 2020 and 2030, by scenario

Figure 11 shows the environmental assessment of video streaming for each device in the three scenarios in 2030. Smart TV has the highest share of CO₂ emissions in all scenarios and the figure shows that the device accounts for a higher share of CO₂ emissions compared to data traffic in 2020, although the share of data traffic increases in 2030 in all scenarios. Therefore, regulatory economic measures that can tackle networks or data centers are of high importance. As people use laptops and PC a lot (higher streaming hours, cf. Table 1) and these have a rather high bitrate, they are placed in the second position, where data traffic constitutes a higher share of energy consumption and corresponding CO₂ emissions. The smartphone plays a much smaller role in CO₂ emissions than video-streaming by TV or

laptop/PC and, similarly to Laptop/PC, data traffic accounts for to a higher share of CO₂ emissions. Tablets play a minor role, as they are barely used for video-streaming. Overall, these findings confirm that the efficiency improvement of data traffic can reduce its CO₂ emissions significantly, and that end-use devices contribute most to the expected future emissions.

6 Discussion and directions for future research

As discussed, the Internet impacts energy consumption and CO₂ emissions through different channels. We already scrutinized how video-streaming with lower resolution can help decrease energy consumption. Such regulatory interventions can be implemented by both mandatory and incentive-based policies. Impacting the behavior of consumers through such ‘nudges’ is one of the short-term practical and low-cost solutions for decreasing the energy consumption of video-streaming. The COVID-19 pandemic is an important factor that has been causing a significant increase of streaming consumption amongst online media subscribers (Lemenager et al., 2021). The long-term behavioral impacts of this (temporary or permanent) shift in video-streaming consumption patterns should be assessed in a further, more detailed analysis of electricity consumption and CO₂ emissions due to video-streaming.

Although resolution adjustments can mitigate the electricity consumption and CO₂ emissions noticeably, adequately designed policies for each end-use device can help to augment the impact further. In addition to lowered resolution, device choice is an indispensable factor that can lead to substantial energy savings and CO₂ mitigation. In particular, TVs and laptops/PCs have high streaming hours and high required resolution. Incentivizing users to stream with other devices can also lead to a significant reduction of electricity consumption of video-streaming. A closer look at subcategories of electricity consumption reveal that the electricity consumption of TV sets is higher than the electricity consumption due to the data traffic. This problem can be addressed by national or EU energy labels, e.g. by forcing TV manufacturers to increase the energy efficiency of their devices. Therefore, we conclude that not only consumers but also government and regulatory bodies are responsible for the achievable electricity- (CO₂-) saving potential.

The rebound effect describes a situation in which potential energy savings due to new technologies with improved energy efficiency is partly offset by user behavior adjustment or systematic factors. Not every streamed video is a perfect substitute for a DVD or CD. But the convenience of video-streaming and portable devices connected to networks can raise the number of video-streaming hours per week. Obviously, such a change in behavior can be expected to reduce other activities – such as reading books, engaging in a conversation, and outdoor activities that have lower electricity consumption and emission intensities. The

network infrastructure of video-streaming is becoming more energy-efficient over time compared to offline activities, although the bitrate of transmitted data is increasing. According to recent studies, bitrates increase faster than energy efficiency, which causes a reduction in greenness gains of online alternatives (Al-Turjman et al., 2017), corroborating our insight that efficiency improvements and greening of the ICT ecosystem may only partially compensate the effects of streaming with a high bitrate. Therefore, technical regulation can play a role to address this problem. A combination of this phenomenon with a rapid increase in the number of subscribers may worsen the problem of traffic congestion. The combination of economic regulation and technical standards may be an option to alleviate this problem considerably.

Moore's law forecasts a 25% annual energy decline per processing unit, or a performance doubling every two years. However, its impact is expected to fade out by 2021–2023 (Shahidi, 2019); (Markov, 2014). This phenomenon has been accounted for in the BAU and the Gray scenario assumptions. Having included Moore's law on detailed components of the data centers substantially increases the robustness of the results. Furthermore, performing a Monte Carlo simulation¹⁷ helps policy-makers and energy analysts to obtain a better understanding of the impact of Moore's law on the system.

One of the limitations of this paper is its neglecting the life-cycle impact of devices for video-streaming, which calls for a life-cycle analysis. The lack of detailed data on user behavior such as resolution choices or membership in streaming platforms, rapid change of equipment features, and the rapid evolution of video-viewing technologies, are other important leading assumptions which have not been addressed in this paper. The second- and end-of-life of devices and data traffic technologies, and technical characteristics of data centers – such as servers, data storage, networks, and infrastructure equipment of DCs – could also be investigated in much more detail. Finally, using detailed data for each European country (or European region) – such as CO₂ emission intensity, or specific user behavior of each country (if any) – can provide further insights regarding regional heterogeneity and enable checking of the validity and robustness of the results.

7 Conclusions and policy implications

This paper presents an estimation of current and expected future electricity consumption, CO₂ emissions, and potential electricity savings from video-streaming in end-use devices, networks, and data centers in Europe from 2020 to 2030. To do so, three scenarios were investigated which are based on specific assumptions regarding energy efficiency gains along the value chain and more optimistic and pessimistic time trends over the decade considered.

¹⁷ Monte Carlo simulation is a method to forecast the outcomes of a model when variables are random.

Simulation results show a great energy-saving potential that consumers and providers of video-streaming can both help to realize. Regarding electricity consumption, reducing streaming hours of users and energy efficiency improvement can lead to a high electricity-saving potential. Simulation results show a 21.2 TWh electricity saving in the Green scenario compared to the BAU scenario. This amount of saving is equivalent to the yearly electricity production of three mid-size baseload coal power plants (~900 MW) and some 8000 full-load hours. The findings confirm a high potential for policy measures targeted at improving energy efficiency and thereby CO₂ reductions.

All scenarios highlight that data traffic has a dominant share in video-streaming, compared to devices. We show that their share will increase noticeably in the future. As an illustration, in the Green scenario which electricity consumption does not increase as in the other scenarios, the share electricity consumption of data traffic increases from 59% in 2020 to 86% in 2030. Accordingly, increasing the energy efficiency by setting reasonable prices for data traffic in the backbone and incentives for data economy on the part of the CPs, can decrease the expected energy consumption markedly.

Based on the common discussions regarding approaching efficiency improvement saturation, we analyze the impact of the increasing number of subscribers and streaming hours in the BAU scenario with and without including electricity efficiency of end-use devices and data traffic sections. Taken together, we demonstrate that energy efficiency gains cannot compensate for the impact of the increasing number of subscribers and streaming hours of users on the absolute electricity consumption. However, we show that electricity consumption is 4 TWh higher with the inclusion of energy efficiency improvements, compared to the situation where no efficiency improvement is assumed.

The findings of this study suggest that technical regulations, in principle, can help to decrease the energy consumption of video-streaming in the short term. An example would be imposing lower resolution of videos on all devices or on selected types of devices. Effective implementation of technical regulations to reduce future electricity consumption not only reduces negative externalities related to CO₂ emissions but also those related to potential network congestion costs. The extent of the latter will depend on the relevance of network scarcities in the ICT ecosystem, which we did not examine in our analysis. Interestingly, in the Green scenario, this policy can lead to a slight decrease of electricity consumption in further years.

For a better understanding of the root causes of service-specific energy consumption in each network segment, we scrutinize the impact of new technologies on the electricity consumption of this segment. Since the penetration of wireless technologies would increase highly

compared to the fixed-line network, we analyze the impact of new technologies – new radio and mm-wave – on total electricity consumption. The present finding suggests that energy efficiency gains (due to autonomous technical change) in wireless technologies alone is insufficient and it can highlight the significance of economic regulation in networks to reduce the electricity consumptions to the utmost. In the Gray scenario, despite using these new technologies, electricity consumption will increase four times in 2030. However, in the Green scenario where the data volume slightly increases, electricity consumption decreases 20% in 2030. DCs are another important part of the network.

Having used a different mix of data center technologies – traditional, cloud, and next generation, we show that energy-efficient data centers as well as networks can help to slightly decrease energy consumption only in the Green scenario. Furthermore, it shows that the relative share of data centers' electricity consumption increases in all scenarios. Regarding CO₂ emissions, due to the hitherto high correlation between the electricity consumption of video-streaming and CO₂ emissions, CO₂ emission trends in the three scenarios mirror the electricity consumption trends (except for the Green scenario, which shows a rather constant trend).

Whereas technical regulations can be considered as rudimentary, “quick fix” remedies to lower energy consumption, such regulations are intrusive and subject to high monitoring costs and do not ensure efficient resource allocation in situations with highly dynamic demand patterns and fast technological development. In contrast, economic regulations in terms of setting a mandatory transit fee for data traffic would induce statically and dynamically efficient outcomes, taking total social costs of service delivery into account, and would hence be the preferable regulatory approach (possibly complemented by technical standards). It is probably safe to assume that in view of efficiency properties a transit fee will achieve at least the same climate benefits as technical regulations while avoiding undesired market distortions. Ideally, such a transit fee provides both incentives to reduce data traffic for content providers and incentives for telecommunications companies to make further investments in data transmission networks (Briglauer et al., 2020). In principle, a transit fee might be set in commercial negotiations between parties. However, given the dominant market position of big streaming providers such negotiations are likely to fail – as telcos' negotiating power is limited. As an interim solution, the regulatory framework might therefore foresee the right (and/or maybe even the obligation) to negotiate with content providers and to obtain support from the national regulatory authority when negotiations with dominant CPs fail (“arbitration fallback”).

The entire Internet ecosystem would become more sustainable if larger originators of traffic were obliged to make an adequate contribution in terms of an appropriate transit fee or an alternative efficient pricing mechanism. A transit fee would not only reduce ICT's carbon

footprint, but it ideally also ensures that more adequate data transmission capacities are provided to safeguard network integrity and the stable, efficient supply of all digital services.

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