Whitepaper

Carbon Footprint Analysis of the RTL+ Video Streaming Service

In 2020, a sharp increase in overall internet traffic by 44 % was observed, largely attributed to the COVID-19 pandemic and changing consumer behavior. In particular, more than 57 % of the global internet traffic can be traced back to online video streaming applications [1]. Due to the reportedly high bandwidth consumption and computing intensive tasks associated with such services, it is of particular interest to investigate the carbon footprint produced by consuming online video content. This whitepaper analyzes the CO2-equivalent (CO2e) greenhouse gas emissions for the German video-on-demand (VOD) and live-streaming service RTL+ (former TVNOW) of RTL Deutschland.

By modeling every aspect of the video transmission system, starting at the in-house processing of ingested video content, further processing and caching by third-party cloud computing services and final delivery to various consumer devices, the total greenhouse gas emissions per hour of streamed content are estimated. Since measures to reduce carbon emissions are already deployed by RTL Deutschland and involved third parties, this study considers two different reporting scenarios in the analysis: For parts of the video streaming architecture, where measures for greenhouse gas emission reductions are already in place and quantifiable data is made available, the reduced carbon emissions are factored in for the overall estimate. To allow benchmarking of the estimate with previous studies and to evaluate the impact of carbon emission reductions, an energy-consumption based calculation respecting the average emissions of the German energy mix for electrical energy is also applied.

Beyond the quantification of carbon emissions, this study aims at identifying technical areas for RTL Deutschland and RTL+ on how to further minimize the carbon footprint of its streaming service as a contribution to the company's carbon reduction target [2]. Factoring in measures to reduce emissions, average overall emissions of about 42.7 g CO2e per hour of streamed video can be reported. A large potential for CO2 reductions is attributed to the customer-side of the video transmission system: raising customer awareness for energy-efficient devices and settings can decrease the carbon footprint. Further optimizations can be applied to the consumer delivery-independent parts of the streaming service, such as employing more efficient computing resource utilization and transmitting video at lower bitrates. At last, the long-term transitioning to green electricity from renewable energy sources will decrease emissions at every part of the transmission system.

Keywords
video streaming, product carbon footprint

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Introduction

The usage of online video has been steadily increasing over the last decade. In Germany, the share of the population which consumes online video at least once on a weekly basis has increased from merely 23 % in 2009 to 61 % in 2019. The COVID-19 pandemic further accelerated this trend, leading to a total share of 69 % in 2020 [3]. Similar developments can be seen globally [1]. Video streaming always has been a demanding application in terms of the total data rates required for transmission. Unlike the typical broadcast (e.g., DVB) and multicast delivery, the now prevalent adaptive streaming via HTTP is a unicast connection, regardless of whether the served stream is VOD or live. Therefore, the total bandwidth share increases with every streaming connection. Undoubtedly, adaptive streaming has the benefit of being able to adapt the video stream to unpredictable bandwidths, different devices and capabilities using client-side adaptation logic. Thus, as of 2020, more than 57 % of all global internet traffic is occupied by data produced from online video streaming [1]. Since such a large share of the global information- and communication technology (ICT) infrastructure is used by internet streaming services, the evaluation of greenhouse gas emissions directly and indirectly produced by such services is of broad interest. A streaming service such as RTL+ is a complex and intricate technical system, involving multiple sub-systems which operate in concert to enable adaptive bitrate streaming to millions of customers over multiple different platforms and device classes. Many of these sub-systems can dynamically scale the required computing resources to the expected demand, e.g., the number of concurrent streaming sessions. Therefore, typical carbon footprint assessments used in ICT try to break down the analysis into the involved sub-systems and estimate the greenhouse gas emissions for each system individually, using data averaged over a certain timespan. In this report, data from April 2021 has been used in the analysis.

Prior Evaluations

The carbon footprint of online video streaming services has garnered much attention in recent years, starting with a report published by the French nonprofit think tank "The Shift Project" in 2019 [4]. In an interview conducted by AFP with one of the collaborators of the report, a number as high as 3200 g/h CO2e was circulated and quickly picked up by media outlets [5]. A later study published by *CarbonBrief* [6], a website funded by the European Climate Foundation, revealed major flaws in the much-cited *Shift Project* report such as errors when converting bitrates to bytes and bad model assumptions. More recent studies by *Carbon Trust* [7], the *International Energy Agency* (IEA) [8] and the German *Umweltbundesamt* [11] seem to converge on much smaller estimates. An overview of recent studies and the reported greenhouse gas emissions per hour of streamed content is given in Table 1. As the spread of different, independent estimates still spans almost two orders of magnitude, it can be assumed that large uncertainties still exist when modeling the carbon footprint of such highly complex technical systems as it is the case for a typical online streaming service. Furthermore, country-specific differences in usage of primary energy sources largely influence the carbon intensity of video streaming and thus are of particular importance. This is exemplified in the recent *Carbon Trust* report by comparing the estimates given for France (10 g/h CO2e), Sweden (3 g/h CO2e) and Germany (76 g/h CO2e). These differences are purely based on different mixtures of primary energy sources. Whereas the base-load electricity production in France and Sweden is dominated by direct emission-free nuclear power (>70 % of total TWh) and a combination of hydro power and nuclear power (>85 % of total TWh), respectively, the German energy mix is still predominantly sourced from fossil fuels.

Table 1: Overview of recent estimates of the carbon intensity for video streaming.

Reference	**Year**	**Carbon Intensity Estimate [g/h CO2e]**
Carbon Trust (Germany) [7]	2020	76
Carbon Trust (EU Average) [7]	2020	56
BBC (UK, iPlayer) [18]	2019 / 2020	33
BBC (UK, IPTV) [18]	2019 / 2020	32
IEA (Germany) [8]	2019	31

Reference	Year	Carbon Intensity Estimate [g/h CO2e]
IEA (Global) [8]	2019	36
BITKOM (Global, 720p, 65" TV) [10]	2018	130
BITKOM (Global, 4K, 65" TV) [10]	2018	610
Shift Project (Global, Updated) [4]	2018	394
Shift Project (Global, AFP Interview) [5]	2018	3200

Researchers from Ericsson recently pointed out, that the usage of energy-per-data figures (e.g. in kWh/GB) in network models used to calculate the energy consumption of specific services based on the total amount of data, as performed in many studies, is problematic, as there is little to no proportionality between power and electricity consumption and data intensity, due to the idling consumption of involved equipment [9]. In fact, such figures may insinuate that more data results in more energy, which is not the case. This study acknowledges this statement and therefore utilizes energy-per-data figures only for allocation purposes and when no better allocation approach was available.

Video Streaming Carbon Footprint Model

As with every carbon footprint assessment, the operational boundary of the analysis must be defined. The quantification of a carbon footprint of a product or service according to ISO 14067 takes into consideration the entire life cycle of the unit under consideration. Beyond emission sources controlled by RTL Deutschland, this also includes emissions in the value chain that are caused by multiple third-party service providers involved in the video streaming transmission. This aspect further complicates the analysis, due to, for example, different reporting methodologies, operational boundaries or levels of detail considered by third-party services that are involved in the video streaming transmission. Some cloud computing providers and internet service providers, for example, do not publish extensive data on accumulated or per-customer greenhouse gas emissions. In these cases, a proxy in combination with heuristics can be utilized to generate an estimate, such as the average computational load measured in (virtual) cores/h. Naturally, such an approach increases the uncertainty in the estimate.

The functional unit assessed in this study is one hour of video streaming service. This study focuses on the technical systems involved in the video streaming transmission chain and the carbon emissions generated by the operation of these systems. Therefore, the actual production of the video content, which by itself can be another large source of emissions, is considered out of the scope of this report. Additionally, the emissions from the production of physical infrastructure and devices are also out of scope. The carbon footprint calculations of this study take into account all greenhouse gases listed in the Kyoto Protocol and are expressed in carbon equivalents applying 100-yr Global Warming Potential.

The carbon footprint for individual parts of the video streaming system is modeled using two different allocation approaches: for in-house and cloud-based processing systems, only the average power consumption of technical infrastructure is considered. These systems, since they are located behind a first caching layer, operate independently of the amount of data being transmitted, e.g., the power consumption is considered nearly identical, whether the streaming service is at base or peak load. A similar assumption is made for the consumer devices. In the second approach, an allocation-based scheme is used, where the greenhouse gas emissions are estimated based on the amount of data being transported. This scheme is applicable for the physical transmission of the video through servers run by content delivery network providers (CDNs) and the internet backbones of internet service providers (ISPs).

In total, four major components of the video streaming service are considered as shown in Equation 1:

- Inhouse services and processing $\boldsymbol{D}_{\mathbf{Inhouse}}$ of video content running on infrastructure under direct control of RTL Deutschland, which includes sub-systems such as media asset management systems and the transcoding of every video asset and live video signals into multiple renditions of varying resolution and bitrate,
- Cloud processing and content-delivery networks $\boldsymbol{D}_{\mathbf{Cloud}}$, which encompasses technical sub-systems such as load balancers, webservices, origin servers and caching of video segments,
- Transport $\boldsymbol{D}_{\mathbf{Transport}}$, which includes the delivery of video segments on physical backbone networks to the customers through fiber optic, copper-based or mobile connections at the last mile,
- Consumer devices $\boldsymbol{D}_{\mathbf{User}}$, which includes TVs, smartphones or laptops used to consume the video as well as additional equipment such as set-top-boxes, digital media players and integrated routers to access the internet.

The total greenhouse gas emissions D_{Total}, giving the carbon intensity estimate of the RTL+ streaming service in grams of CO2e emissions per hour of streamed video content, are thus computed as the summation over each individual contribution in the processing and transmission chain:

$$D_{\text{Total}} = D_{\text{Inhouse}} + D_{\text{Cloud}} + D_{\text{Transport}} + D_{\text{User}} \qquad 1$$

Inhouse Processing

The inhouse processing, which is performed at the local datacenter at the RTL headquarter in Cologne, Germany, is modeled by considering the total energy consumption of the local computing infrastructure E_{Inhouse}, the greenhouse gas emissions for electricity as provided by a local electricity utility C_{Inhouse} and the total hours of streamed content T_{Content} for the given time span:

$$D_{\text{Inhouse}} = \frac{E_{\text{Inhouse}} \cdot C_{\text{Inhouse}}}{T_{\text{Content}}} \qquad 2$$

Cloud and Content Delivery Networks

The contribution of cloud and content delivery networks D_{Cloud} is modeled by a heuristic approach for infrastructure components which are independent of the amount of video data being streamed, D_{Static}, and by using emission data $D_{\text{CDN}}(R_{\text{Content}}, \mathrm{T}_{\text{Content}})$ as provided by CDNs, depending on the average video bitrate R_{Content} and the total hours of video being streamed $\mathrm{T}_{\text{Content}}$:

$$D_{\text{Cloud}} = D_{\text{Static}} + D_{\text{CDN}}(R_{\text{Content}}, \mathrm{T}_{\text{Content}}) \qquad 3$$

Transport

For the contribution to the total emissions produced by transporting data from the CDN servers to the customers $D_{\text{Transport}}$, two components are considered: For traversing large distances, data is typically routed through the fiberoptic-based internet backbone. This contribution is denoted as $D_{\text{Backbone}}(R_{\text{Content}}, \mathrm{T}_{\text{Content}})$ which again depends on the total volume of data being transported. A second contribution $D_{\text{LastMile}}(p_{\text{Connection}})$ is produced by the "last mile" connection of the consumer, which could be a fixed broadband or mobile connection, resulting in different CO2e emissions. Thus, the probability distribution $p_{\text{Connection}}$, $0 \leq p_{\text{Connection}} \leq 1$, describes how consumers access the streaming service. The total emission contribution by the transport of video content to the consumer can now be modeled as follows:

$$D_{\text{Transport}} = D_{\text{Backbone}}(R_{\text{Content}}, \mathrm{T}_{\text{Content}}) + D_{\text{LastMile}}(p_{\text{Connection}}) \qquad 4$$

Consumer Devices

At last, the study considers the emissions produced by customer premises equipment (CPE), required to consume the content. The distribution of consumer device classes p_{Device} (TVs, phones, PCs, and tablets), internet access equipment and their respective energy consumption E_{Device} per hour is computed to estimate the average consumer greenhouse gas emissions. For simplicity and ease of calculation, the power consumption of CPE is considered to be independent of the streamed bitrate and other technical properties of the video stream. It is to be noted that this assumption does not hold in reality and that the relation between power consumption and video stream properties becomes increasingly relevant for lower power playback devices, such as mobile phones, as shown by Herglotz et al. [14]. This modeling inaccuracy is acceptable, due to the usage of conservative estimates for the average power consumption of playback devices. Lastly, to model the potential influence of the consumers on their electricity supply (e.g., own photovoltaic generation, choosing a renewable electricity provider), a customer-based emission factor C_{Consumer} is also included:

$$D_{\text{User}} = C_{\text{Consumer}} \cdot \sum\nolimits_{\text{Devices}} E_{\text{Device}} \cdot p_{\text{Device}} \qquad 5$$

Results

Location-based and Market-based Model Assumptions

Measures to reduce carbon emissions are already being employed by RTL and other third parties. These measures, for example, may include the purchase of green electricity for datacenters. To reflect these measures, two reporting methods are being distinguished in this study: Reduced carbon emissions, wherever data is available, are subsumed as *market-based* carbon emissions. In the second, *location-based* approach, carbon emissions are estimated based on the demand of electrical energy and the average emission intensity of the German electricity grid. This distinction between market-based and location-based greenhouse gas emissions follows the recommendation given by the Scope 2 Guidance of the Greenhouse Gas Protocol (GHG) [27].

For modeling the emissions produced by in-house technical infrastructure and by the consumer, estimates for the emission intensity factors C_{Inhouse} and C_{Consumer} are required. Here, different values for the carbon emissions intensities can reflect market-based and location-based differences for electrical energy. For Germany, a carbon emission intensity factor of $C_{\text{Ger,Mix}}$ = 375 g CO2e / kWh is presumed [13]. This figure corresponds to the average German emissions of 2020[1], excluding indirect upstream emissions. Thus, for the location-based estimates shown in Table 2, $C_{\text{Inhouse}} \equiv C_{\text{Ger,Mix}}$ is used.

RTL Deutschland actively reduces or compensates emissions (e.g., through the purchase of electricity from renewable sources or carbon emission certificates). The datacenter, offices and studios located at the broadcasting headquarter in Cologne, Germany, are powered by renewable energies. Thus, for the market-based estimates, a carbon emission factor of $C_{\text{Inhouse}} = 0$ can be applied.

Cloud-based computing services that are part of the backend of RTL+, which may include hosting of servers, databases, storage, or networking, are mostly operated by third party services. Thus, the model depends on data that was provided by those operators.

For the emissions produced by the backbone network during transmission, publicly available data is used, such as the carbon intensity ESG-KPIs reported by the Deutsche Telekom AG for Germany [15]. More than 30 % of RTL+ customers use Deutsche Telekom AG as their internet service provider.

At the last mile, most of the consumers access RTL+ using a wired broadband internet connection. It is therefore conservatively assumed that 10 % of consumers access content from mobile networks directly. Carbon intensity estimates of individual internet access methods published by the Umweltbundesamt [11] are used for the modeling.

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[1] As mentioned above, the projected carbon emissions for 2021 are expected to be closer to the value for 2019 than for the skewed value reported for 2020.

Of course, a market-based allocation of emissions due to energy required by consumer devices reflecting individual choices in utility providers or other factors influencing the personal carbon emission intensity (e.g., own photovoltaic generation, usage of cogeneration / combined heat and power) is inherently not possible. Therefore, for consumer generated emissions shown in Table 2 and 3, a value of $C_{\text{Consumer}} \equiv C_{\text{Ger,Mix}}$ is always assumed.

Average emissions

The analysis finds that on average, about 42.7 g CO2e are emitted when streaming one hour of video content on RTL+ for an average bitrate of 5.43 Mbit/s. This estimate takes market-based emissions into consideration, except for the emissions generated by the consumer. The location-based estimate finds that on average, 92.3 g CO2e are emitted per hour of streamed video content. This figure is in the same range as the estimate provided by the recent Carbon Trust study for Germany.

Regardless of market-based or location-based allocation methodologies, the smallest share is contributed to the total emissions by inhouse services and processing, measured at D_{Inhouse} = 0.4 g CO2e/h when computed for the emission intensity of the German national power grid and zero when computed for the actual green energy provider. Cloud-services, including content delivery networks, also contribute a minor share of emissions, measured at D_{Cloud} = 0.8 g CO2e/h (market-based) and D_{Cloud} = 1.5 g CO2e/h (location-based).

The emissions that occur during transport of video data to the consumer contribute $D_{\text{Transport}}$ = 11.1 g CO2e/h (market-based) and $D_{\text{Transport}}$ = 59.5 g CO2e/h (locating-based), which includes all emissions from backbone networks and fixed-broadband or mobile last mile connections. The large difference between market- and location-based estimates clearly indicates the decarbonization efforts undertaken by network providers.

For the market-based approach, the overall largest share of emissions is contributed by devices run by the consumer. By respecting the distribution of customers using TVs, smartphones, PCs, or laptops and tablets, average emissions of 30.9 g CO2e/h are reported, making up the majority of all emissions. For individual device types however, the emissions can vary widely due to different demands of electrical power. While a customer watching content on a typical TV requires the most power and thus generates about 37.5 g CO2e/h for a typical 100 W rated TV alone, a customer watching content on a smartphone generates only 0.4 g CO2e/h. Additional power is required for peripheral devices, such as wireless routers, media players such as FireTVs, AppleTVs, or set-top boxes with VoD capabilities. These devices generate an additional 4.5 g CO2e/h, regardless of the device class used for video consumption. It is to be noted that this estimate differs from other studies such as [7], which assumes an energy consumption of 71 Wh for routers per streaming hour, due to a different allocation scheme. While [7] allocates router energy based on the ratio of streamed data and total average data volume, this study allocates router energy based on the actual physical usage of the device per streaming hour. Thus, scenarios where a router is not actively used but powered on, or used by another service concurrently during streaming, are not considered.

Table 2: Average CO2e emissions for the RTL+ streaming service by component.

Component	**Average CO2e emissions by component in g/h**	
	Market-based (actual)	**Location-based**
D_{Inhouse}	0.0	0.4
D_{Cloud}	0.8	1.5
$D_{\text{Transport}}$	11.1	59.5
D_{User}	30.9	30.9
$\boldsymbol{D_{\text{Total}}}$[2]	**42.7**	**92.3**

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[2] Totals may not sum due to rounding.

Table 3: Average CO2e emissions and power consumption by device class.

Device Class	Average D_{User} CO2e emissions and typical power consumption per device class	
	D_{User} CO2e emissions [g/h CO2e]	Power consumption [W]
TV	37.5	100.0
Phone	0.4	1.0
PC	25.7	68.5
Tablet	1.9	5.0
Periph.	4.5	12.0
Weighted Average[2]	**30.9**	**82.3**

Comparison and Reducing Emissions

Comparing the emissions produced due to streaming video with those produced by classical broadcast is inherently difficult, due to the different technologies being involved. Digital television broadcast signals are typically delivered via satellite (DVB-S/S2), cable (DVB-C), or terrestrial radio (DVB-T2). As shown by a recent study published by BBC Research [18], the operational emissions produced by satellite television during transport can be neglected, considering the vast, continent-spanning areas and therefore huge number of customers that can be served by a satellite transponder within its footprint, such as Astra 19.2°E.

The technical infrastructure required for cable television (DVB-C) is structured similarly to the broadband/DSL infrastructure and can be assessed accordingly, see also III c. The television signal is sent via satellite or fiber optic cable to cable headends via central distribution centers and is then fed into the respective cable network and distributed to households via broadband cable.

For the reception of DVB-T2, the first thing to mention is the operation of the transmitters and antennas that supply locally limited areas. In Germany, such transmitters are operated at more than 50 locations. Considering that a strategically well-placed transmitter with an effective radiated power of up to 50 kW can transport many DVB-T2 television programs to millions of customers, the greenhouse gas emissions per hour of consumed video content are correspondingly low, as for the case of satellite broadcast [19].

To help clarify the importance of individual distribution paths (DVB-S/S2/C/T2) in Germany, the technical reach shall be mentioned in conclusion: Most German households receive the TV signal via cable (43.7 %) or satellite (43.5 %), while terrestrial distribution plays only a minor role with 6.7 % [33].

As can be seen in this study, the carbon footprint per hour of content viewed is mainly determined by the consumer playback devices and other CPEs (customer premise equipment). Access to IPTV offerings from large platform operators such as Telekom and Vodafone is usually realized via an operator set-top box (OSTB). The number of set-top boxes (STB) used for linear broadcasting is declining, as most TV sets are already equipped with a DVB-S/S2/C/T2 tuner. In general, it should be noted that newer STB models are significantly more energy efficient than earlier, power-hungry models [18]. For digital terrestrial reception, customers often operate additional active antenna amplifiers to increase signal strength. These devices are usually in operation permanently and therefore contribute significantly to the overall energy consumption, similar to devices required for internet access.

Considering that DVB signals are almost exclusively consumed on larger TV screens, the average power consumption (compare Table 3) for a linear broadcast consumer is presumably higher than for a streaming consumer, who views content more frequently on smartphones, tablets and laptops with low power consumption. However, current trends also indicate that the use of OTT content on TV sets is steadily increasing and thus converging with the behavior of linear broadcast users [33].

An exemplary study of the energy consumption of individual distribution channels was performed by BBC Research, specifically taking into account the technical differences between linear broadcast and streaming [34]. The study concludes that the energy consumption of video streaming per hour (0.19 kWh) is actually similar to that of satellite (0.16 kWh) and cable TV (0.15 kWh) while terrestrial distribution (0.06 kWh) has the lowest energy consumption per hour. It must be emphasized, however, that these figures are not directly transferable to Germany, as they are based on different technical reach and other assumptions about usage.

In summary, these results signify that all distribution channels have potential to reduce greenhouse gas emissions. For the case of online video streaming, the following options can be considered:

At the backend of the streaming service, more efficient encoding of video content for example, achievable trough usage of newer video compression technologies or better adaptation of bitrates to specific content and device capabilities (*content-* and *context-aware* encoding), can lower the necessary bandwidth by up to 50 %, while still maintaining high video quality. By also factoring in the power consumption of user devices, an optimization trilemma is created: The goals of providing video streams with high quality of experience (QoE) at low bitrates and low energy consumption are conflicting and improving one aspect can only be realized by accepting losses in other aspects and vice versa. A recent study by Herglotz and Robitza et al. [17] has however shown that there is huge potential in optimizing the overall energy consumption of end-user devices while keeping QoE high, proving that such operating points exist.

An overall lower data volume required to serve video content may trickle down the transmission chain and has the potential to produce less carbon emissions at the delivery-related parts of the system. However, the actual net impact might be difficult to forecast and quantify. As pointed out by Malmodin [9], there is little to no correlation between data volume and power consumption in the ICT sector. In fact, the volume of data transported over the internet has increased by many orders of magnitude, while the energy consumption has not, showing rapid technological improvements in terms of energy efficiency per data volume.
More efficient encoding processes often require substantially more computing power for transcoding, partly cannibalizing reductions of carbon emissions that might be achievable due to less overall data that needs to be transported to each consumer. For the transition from Advanced Video Coding (H.264/AVC) to High Efficiency Video Coding (H.265/HEVC) for example, encoding time roughly quadruples for a 50 % decrease in bitrate. Economic considerations might also prohibit the large-scale deployment of content- and context-aware encoding.

Without switching to newer codecs, the average bitrate can be safely decreased for small-screen mobile devices by limiting the maximum delivered resolution of the video content, without a noticeable loss in visual quality, while at the same time prolonging battery life. Although modern smartphones have extremely high-resolution displays, even capable of natively showing 4K UHD content, the maximum angular resolution of the human eye and the viewing conditions set a physical limit to the maximum perceivable video resolution. Typically, delivering video beyond 720p resolution to small screen devices leads to no perceivable gain in visual quality.

Measures to reduce carbon emissions are already undertaken by third parties involved in video streaming. The global CDN provider Akamai reports achieving a 50 % share of renewable energies for 2020 [20]. Similarly, Amazon Web Services (AWS) pledges to power their global technical infrastructure with 100 % renewable energies by 2025 [21]. All major German internet service providers including Deutsche Telekom, Vodafone, O2/Telefonica are committed to 100 % renewable energy programs, and targeting carbon neutrality with net-zero greenhouse gas emissions by 2025 [15][22][23].

These pledges to reduce carbon emissions are not only achieved through the increased usage of green energy but also backed by technological evolution and innovation. For the

transport component of video data, for example, reductions in carbon emissions are achievable through more energy-efficient technologies currently being implemented. For wired internet access, optical networks (e.g., *fiber-to-the-home*) not only provide higher bandwidth to consumers compared to copper- or coax-based access, but also use less energy [25][11].
Wireless access to the internet on the other hand will be dominated in the future by 5G. Although individual base stations are reported to require more power compared to LTE, there is an overarching consensus that 5G offers a significant energy efficiency increase. Energy efficiency improvements in the range of 90 % are reported by major 5G network equipment manufacturers [28][29]. We further refer to [26] for a meta-study on the energy usage implications of 5G.

A large potential for reducing carbon emissions is located at the consumer-side: Since the energy-consumption of consumer devices has the largest impact on CO2 emissions, raising awareness for the topics of energy efficiency and the influence of usage behavior is of great importance. In general, the energy consumption label for electrical appliances according to EU Regulation 2017/1369 ("EU energy label") provides information on the average energy consumption and provides an energy efficiency class rating between "A+++" and "G" for each appliance. The energy efficiency of TV sets has improved significantly over the past 10 years. Whereas in 2013, 49 % of all devices were rated in class "A" or better, the figure increased to 94 % by 2019 [32]. However, specifically for electronic displays, a revised EU energy label according to EU Regulation 2019/2013 came into force in March 2021, containing a modified efficiency scale. This revised scale has led to a downgrading of all TV sets into significantly worse efficiency classes. In particular, TVs with large screens are now almost exclusively found in classes F and G. The top-class A remains free to leave room for technical progress and to create an additional incentive for manufacturers.

For consumers, the following aspects arise in terms of energy consumption and usage:

- **The screen size is the decisive factor for overall power consumption. The optimal screen size not only depends on personal preference, but also on the external viewing conditions (distance from the device).**
- **The new EU energy consumption label for TVs provides separate information about the power requirements when playing SDR and HDR content. However, energy consumption in HDR mode, which is often specified as significantly higher, also depends on the displayed content and its dynamic range.**
- **Devices without built-in tuners / internet access are automatically rated better because the power consumption is lower, but additional set-top boxes or speakers consume more energy overall compared to "all-in-one" devices [35].**
- **Modern TVs offer a variety of energy-saving settings. Automatic brightness control (ABC) optimally adjusts the screen brightness to the existing ambient light intensity and leads to lower energy consumption [31]. Furthermore, the picture mode can often be selected in categories from e.g. "Economy" to "Dynamic", which also has an effect on power consumption.**
- **Prolonged usage of lower power devices such as smartphones and laptops, where the emissions from manufacturing accounts for the most significant part of the total life-cycle carbon footprint [30].**

Finally, the necessary increase of the share of renewable electricity in the national grid and local renewable electricity generation (e.g., photovoltaic) will significantly drive carbon emission reductions at the consumer side.

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