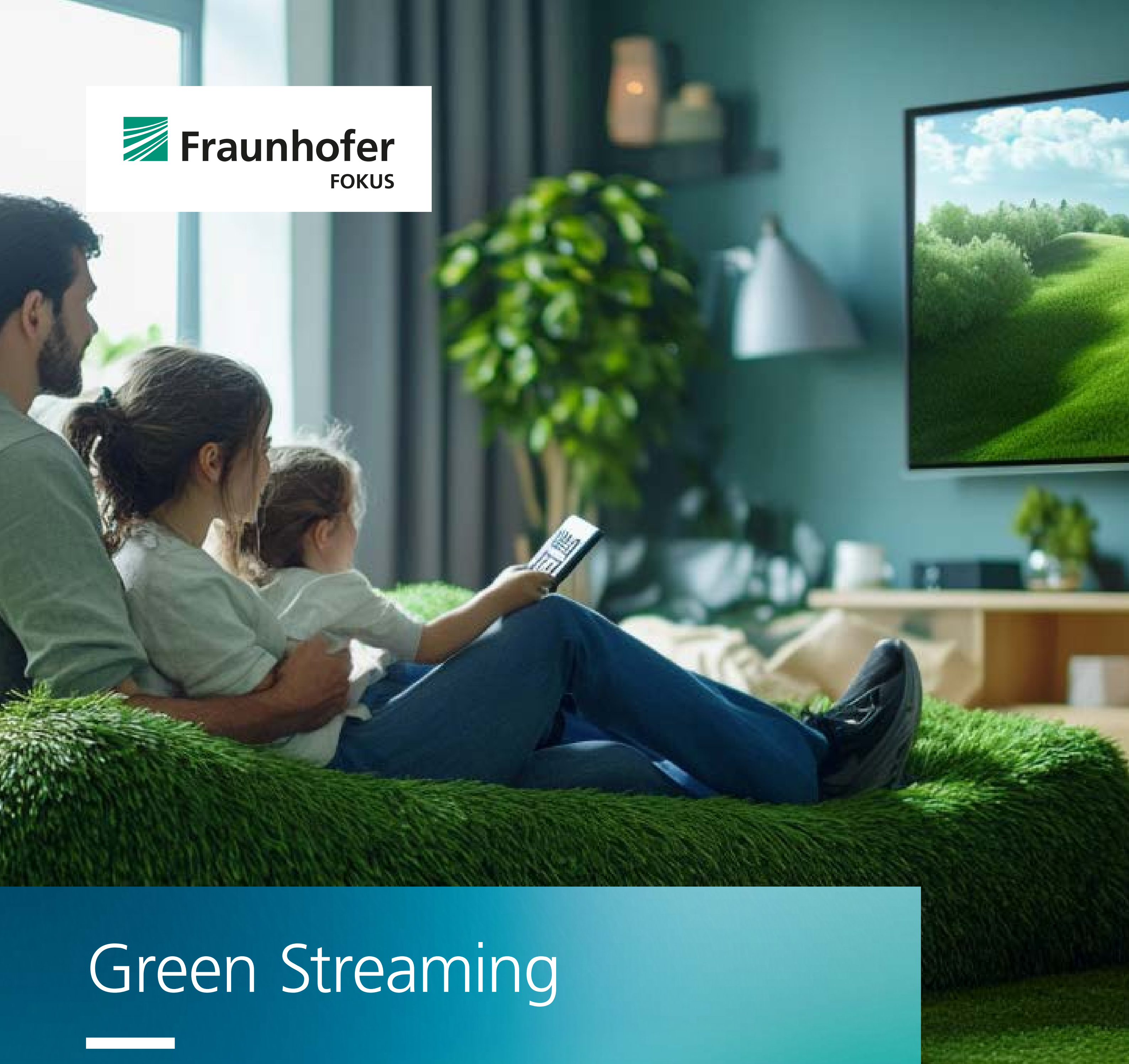


Green Streaming

Guidelines on Evaluating the Energy Consumption and Reducing the CO_2 Emissions of Video Streaming

Contents

> **"If you can't measure it, you can't improve it."**
>
> Lord Kelvin (1824-1907)

1. Introduction

Media companies, video streaming providers and TV stations need to be able to understand and evaluate the environmental footprint of their video streaming services. Standardized and transparent measurement methods, models and metrics are crucial in helping them achieve this.

Video streaming has become an integral part of our daily media consumption and accounts for the majority (60 to 70 percent) of global internet data traffic. With the growing popularity of streaming services and the extensive use of video content on social media platforms, it is more important than ever to be able to understand and evaluate the impact of this technology on our environment. This white paper examines the streaming value chain and its environmental footprint, from the content production stage to customers' end devices. To this end, it considers the energy consumption involved in video streaming and the resulting greenhouse gas emissions along the value chain.

The aim of the Green Streaming project funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) is to verify and analyze the existing studies, which are often based on simulations, by performing measurements along the streaming value chain. In cases where direct measurements are not possible or measurement results cannot be clearly attributed to a process involved in the value chain, established computational models are used and explained as a way of representing the relevant components. Suitable measuring points along the streaming value chain are defined for this purpose and aspects including AV processing, contribution, distribution and playback on users' devices are taken into account.

This information is then used as a basis to identify potential for savings and optimization, and technical solutions are developed and tested with the aim of reducing the amount of energy required. The results of this analysis provide the foundation for this white paper.

The white paper provides guidelines to help decision makers, developers and consumers identify the complex and diverse relationships between streaming components and environmental impact, and promote sustainable solutions. It provides an in-depth insight into the latest research findings, the methodologies used to calculate electrical energy consumption and emissions and the importance of efficient hardware for the individual components in the streaming value chain.

2. Current state of research and resulting approach for Green Streaming

The streaming value chain is a complex system made up of numerous subcomponents. Examining this system requires different approaches and models depending on the usage scenario in question

2.1 Scientific findings to date

Numerous research projects, committees (IEA, GSMA, ETNO, NGMA, DIMPACT, etc.) and studies have focused on quantifying the electrical energy consumption involved in using streaming services and the size of the carbon footprint associated with video streaming. In some cases, these studies deliver widely differing and contradictory results due to the different methods, assumptions and data sets used. As a result, it is virtually impossible to compare the values published for the electrical energy consumption or carbon footprint.

One finding of the literature review is that the values calculated for the energy consumption and CO_2 emissions of streaming services can vary significantly depending on the models used, the means of transmission, the end device used, the usage habits of consumers and the electricity mix in question.

One of the key contributions to this area of research is the white paper entitled "Carbon impact of video streaming" by the Carbon Trust in collaboration with DIMPACT [1]. Using the DIMPACT model, the white paper calculates an average carbon footprint of 55 g of CO_2e per hour of video streaming for Europe. It also states that video streaming has a low carbon footprint in comparison with other human activities.

The media company RTL Deutschland carried out a study into the environmental impact of its video streaming service (RTL+). The study analyzed the emissions of various components including internal processing, the use of cloud services, transport and end devices. The results show that streaming video content on RTL+ — at an average bitrate of 5.43 Mbit/s — causes around 42.7 g of CO_2e (without the emissions generated by the consumers) from a market-based perspective. The location-based estimate is around 92.3 g of CO_2e per hour. The end devices account for 30.9 g of CO_2e per hour within the figure for the total emissions. [2] Other important sources describe in detail the two main models used to calculate energy consumption in networks: the energy intensity model [3] and the power model [4].

In summary, the following conclusions can be drawn from the literature sources:

- The streaming value chain is a complex digital and physical system with numerous dependencies and a wide range of market participants.
- Even though data volumes have risen sharply in recent years, the energy consumption of the distribution networks have only seen a marginal increase.
- The fact that reports often simply cite the energy intensity in kWh/GB leads to the assumption that the total amount of energy required is proportional to the data traffic. This is not the case in reality and provides an inadequate basis for a more detailed analysis.
- Many experts therefore suggest a time-based metric when stating the amount of energy required for video streaming (kWh per hour of video streaming) [4] [5].
- The majority of the energy in the streaming value chain (approx. 70–80 percent) is consumed by the end devices (smart TVs, customer-premises equipment (CPE), etc.) of the users [1].
- Distribution networks still require a large amount of energy even when no data is being transmitted ("idle load"). According to estimates, this idle load accounts for 50 to 70 percent of their total energy consumption.
- With regard to electrical energy consumption, fiber-optic technology is the most efficient option for distributing streaming content. [6]

2.2 Terminology and methods

The literature review has shown that the calculated energy consumption values and CO_2 emissions of streaming services can vary significantly. This variability depends on various factors including the models used, the means of transmission, the end device, the usage habits of consumers and the underlying electricity mix. Green Streaming's aim is to use measurements to analyze and validate the available data. The results are to be presented in a transparent, comprehensible manner and discussed in the context of optimization potential for a more sustainable, energy-efficient streaming value chain. The following sections therefore explain the key methods, terminology and KPIs as well as the influence of different usage scenarios.

2.2.1 Methods

Various methods and models are used to determine the CO_2 emissions of streaming services. The most important ones include:

– **Energy intensity model:** The energy intensity model is the conventional model for calculating the amount of electricity consumed during data transmission. It states the amount of energy required per data volume transmitted in kWh/GB and is cited by many network operators as a KPI in their ESG reports.
– **Power model:** The power model works on the assumption that the amount of energy required is time-dependent and that a large proportion of the energy is consumed even when no data is being transmitted; i.e., distribution networks have a high idle load due to the fact that the components are operated 24/7. An additional slight increase in the energy consumption during data transmission is often modeled.
– **Electrical energy consumption measurements:** Direct measurements of the electrical energy consumption of various components in the streaming value chain, such as servers, network equipment and end devices, to make sure that the data determined is as accurate as possible.
– **Life cycle assessment (LCA):** A comprehensive method for assessing the environmental impact of a product or service over its entire life cycle, from the raw materials to production, use and ultimately disposal.
– **Product carbon footprint (PCF):** The carbon footprint of a product, comprising all of the emissions that occur throughout its entire life cycle.
– **Allocation:** The act of assigning environmental impact to various products or services that are produced together or use common structures.

2.2.2 Terms

– **Functional unit:** A defined quantity of a product or service that is used as the basis for calculating the environmental impact.
– **System boundary:** The boundary within which the environmental impact of a product or service is evaluated.
– **Embodied emissions:** The emissions that are caused during the production, transport and disposal of a product.
– **CO_2 equivalent:** A unit of measurement that is used to compare the impact of different greenhouse gases on the climate by converting them to equivalent quantities of CO_2. Note: The term "CO_2 emissions" is used in this report for reasons of simplicity but always refers to the entire greenhouse gas balance in CO_2 equivalents.
– **Electrical energy consumption:** Refers to usage figures from an electric-only perspective.
– **Energy consumption:** Takes into account other forms of energy in addition to electrical energy.

2.2.3 KPIs

The main key performance indicators for the energy consumption of video streaming are listed below:

- **Energy intensity** refers to the amount of energy required per data volume transmitted and is expressed in kWh/GB or kWh/TB.
- **Carbon footprint** refers to the quantity of CO_2-equivalent emissions per functional unit and is expressed in kg of CO_2e/unit.
- **Energy per subscriber line/connection:** The amount of energy required for a data connection defined in W/line.
- **Energy consumption per hour of video streaming:** Reference value for the amount of energy required in an hour of video streaming, expressed in W or kW.
- **Carbon footprint per hour of video streaming** measured in g of CO_2e.
- **Energy consumption per end device hour:** The amount of energy required for one end device (smart TV) or piece of customer-premises equipment (CPE) in W per hour of use.
- **PUE value (power usage effectiveness):** A way of measuring the energy efficiency of data centers which states the ratio between the total amount of energy required for a data center and the energy actually used for the IT equipment.

2.3 Influence of different usage scenarios on electrical energy consumption

Alongside our plans to carry out detailed measurements on the components over the course of the project, we will also be analyzing the CO_2 emissions for different usage scenarios. The number of viewers and their choice of end device and transmission network can have a significant impact on the amount of energy required for video streaming. In order to investigate this relationship, we will be looking at five idealized usage scenarios and determining the CO_2 emissions for one hour of video streaming in each case.

Allocation based on viewers

The streaming value chain comprises various components including ingest, encoding, content delivery networks (CDNs), core and access network, and end devices. In order to calculate the total electrical energy consumption and the resulting CO_2 emissions per hour of video streaming on one end device, it is important to understand the electrical energy consumption of the individual components in detail. Furthermore, the proportional energy consumption need to be allocated to the individual streams. As we are looking at the emissions for one hour of video streaming on one end device in this case, we divide the emissions that occur at the start of the streaming value chain (i.e., production infrastructure in the case of live streams, plus ingest and encoding) by the number of viewers to obtain the correct allocation. All other components of the streaming value chain are scaled with the number of viewers; i.e., they each appear once in the footprint per hour of video streaming on one end device.

Usage scenarios

Section 5 looks at the emissions from five idealized usage scenarios; the detailed assumptions for the respective scenarios can be found in the appendix. They differ with regard to the number of viewers, the type of content (live or VOD), the encoding strategy, the transmission network and the end device. In each case, appropriate parameters are selected in order to determine a minimum and maximum electrical energy consumption value. The usage scenarios featured here are idealized on the basis of the assumption that all viewers behave the same way with regard to their chosen resolution and the end device.

Sensitivity analysis

An initial assessment shows how sensitive the relevance of individual components is to changes in the usage figures. This sensitivity analysis is crucial to understanding the impact of changes in use on the total electrical energy consumption and the CO_2 emissions. A detailed analysis will be carried out over the course of the project in order to further evaluate the potential for optimization.

Influence of type of content

Measurements also need to be taken with different types of content in order to evaluate the way in which the content type may influence the amount of energy required. This covers both the use of streaming content and the optimization potential of content-aware encoding. The type of content and the selected encoding strategy can influence the amount of energy required as different content types have different requirements when it comes to data transmission and processing.

Influencing factors

- Usage scenarios have a significant impact on the electrical energy consumption of streaming activities.
- In the case of live streaming, the production infrastructure must be taken into account.
- Allocation of the electrical energy consumption for individual value chain components is required. There are inaccuracies resulting from the attribution problem.
- Usage scenarios make it possible to estimate minimum and maximum electrical energy consumption values.

2.4 Resulting approach

Based on the findings of the research to date, the project will be pursuing a holistic approach with regard to evaluating and reducing the CO_2 emissions of streaming services. This approach comprises a number of key components:

1. **Detailed analysis of the entire streaming value chain**: From content production to data transmission and use by the end consumers. All relevant components and processes are taken into account in order to obtain a complete picture of the energy consumption and the resulting CO_2 emissions.
2. **Electrical energy consumption measurements:** Determining the energy consumption by taking measurements at the individual components along the streaming chain as well as collecting and analyzing existing operating data relating to electrical energy consumption.
3. **Definition of criteria for sustainable video streaming:** Making users aware of the environmental impact of their media consumption behavior and promoting sustainable usage patterns can make a significant contribution toward sustainable, energy-efficient streaming.
4. **Development of a digital green twin:** A digital model of the entire streaming value chain that is used to simulate and optimize the streaming processes. This digital twin makes it possible to test out various scenarios and identify the most efficient and environmentally friendly solutions.
5. **Development of a accounting tool for video streaming:** A CO_2 accounting tool that builds on the scientific findings of the project will make it easier for streaming providers to create sustainability reports and will provide viewers with information about the impact of their media consumption.
6. **Collaboration between industry and research:** The project is aiming to promote close collaboration between content providers, platform operators, end device manufacturers, research institutions and political decision makers. Key examples of relevant associations, organizations and projects include Deutsche TV-Plattform, Bitkom, ZVEI, Greening of Streaming, Ecoflow and the DIMPACT Forum.

3. The streaming value chain

A holistic assessment of the energy consumption of video streaming requires an understanding of the subcomponents and their proportional effect on the streaming value chain as a whole.

3.1 Definition of the streaming value chain

The streaming value chain comprises all steps and components that are required in order to transmit video content from the source to the end consumer. It is made up of the ingest process, encoding, the content delivery network (CDN), the core and access network and the end devices (Figure 1). Each of these steps contributes to the total electrical energy consumption and is examined in detail in the analysis. This section looks at the different variables which influence the electrical energy consumption within this chain and defines the scope of the analysis.

Ingest and encoding

The ingest process refers to the provision of video content on the servers of the streaming services. Encoding is the process of converting this content into various formats and resolutions in order to make it available for different end devices and bandwidths.

Content delivery networks (CDNs)

CDNs are specialized networks which distribute content to end users efficiently. They reduce latency, improve loading speed and cut down data traffic in the core network by placing content on servers that are geographically closer to the users. The electrical energy consumption of CDNs depends on factors such as the number of servers and their geographical distribution.

Core network

The core network forms the backbone of the data transmission process and consists of components such as routers, switches and data centers which allow the streams to be forwarded efficiently and reliably.

Access network

When it comes to the access network, a distinction is made between broadband and broadcast networks. OTT video streaming takes place via broadband technologies using fixed networks (DSL, VDSL, cable, fiber optics) and mobile communications networks (LTE, 5G). Broadcast networks use terrestrial technology (DTT — digital terrestrial television), cable networks or satellite technology. The CPEs (customer-premises equipment) used by the customers, such as routers and modems, are allocated to the access network here.

End devices

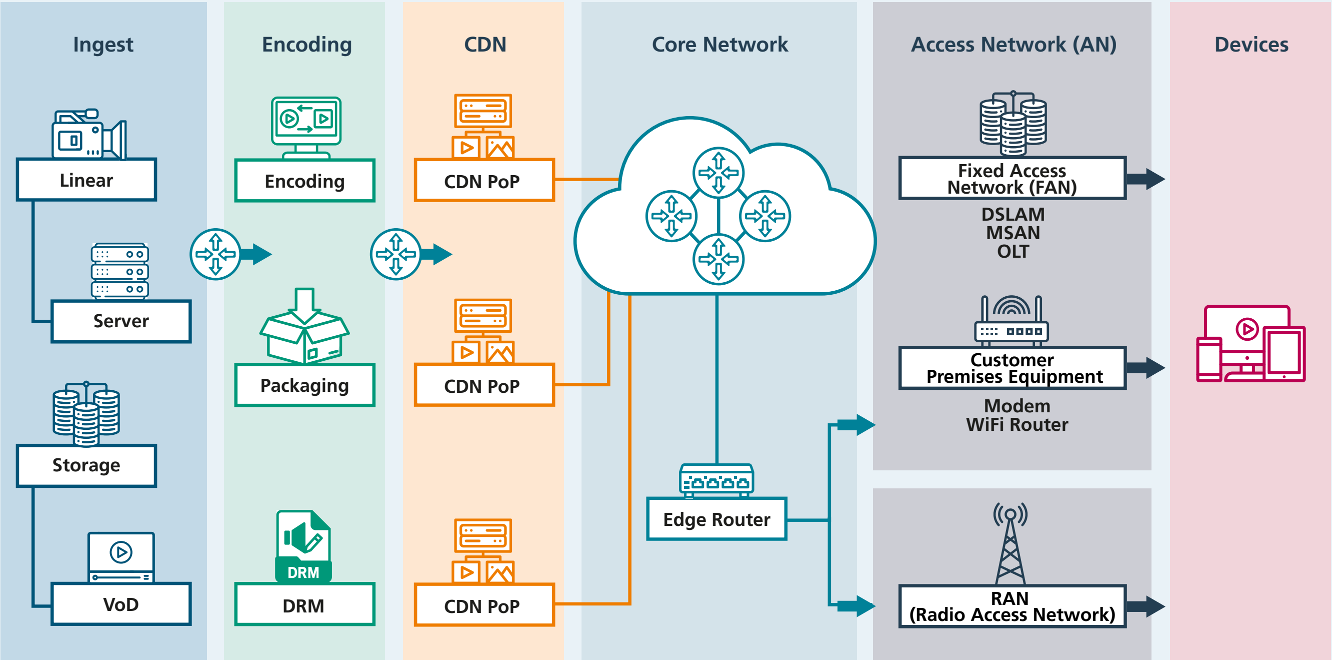
End devices such as smart TVs, computers, tablets and smartphones are the final links in the value chain. The electrical energy consumption of these devices is directly linked to usage behavior and usage duration. They are used in their millions to stream content and account for a significant proportion of the total energy consumption of video streaming.

3.2 Scope of the analysis

The analysis focuses exclusively on the electrical energy consumption of the components specified above and does not include other factors such as standby energy or multiple use of devices. The aim is to paint a clear picture of energy distribution within the value chain and to identify potential savings.

By looking at the whole process chain – from content creation to encoding and distribution, right through to the end devices – targeted measures can be developed to reduce CO_2 emissions. Integrating a comprehensive measurement infrastructure makes it possible to determine the actual energy consumption values and emissions accurately and identify sustainable solutions.

Figure 1: Streaming Supply Chain



4. Results

Usage scenarios and the number of viewers affect the evaluation of video streaming energy consumption and CO2 emissions.

To begin with, the results are compiled and discussed on the basis of the key subcomponents of the streaming value chain. An end-to-end analysis is then carried out with the aid of selected usage scenarios. Taking this information as a basis, energy consumption are determined and CO_2 emissions are derived.

4.1 Production infrastructure

When it comes to analyzing live productions, we will distinguish between conventional studio production, OB van production, remote production and cloud production (Figure 2). The aim of the measurements is to compare the energy consumption and emissions of the different types of production in order to assess whether, and to what extent, the energy consumption can be reduced and CO_2 saved through the choice of production type. When remote production is used for live broadcasts, the video and audio signals are captured on site at the event but processing and production take place at a central, remote location such as a broadcasting center. A proof of concept was carried out for a live production, based on a German second-league football match, and measurements were taken to determine the energy consumption. The setup involved seven cameras on site along with an SMPTE ST 2110-compliant control room and a central equipment room (CER) at a remote location – corresponding to a regular TV production setup and ensuring appropriate broadcast quality.

Apart from the camera technology, the only technical equipment at the event location was a compact 12U rack flight case ("stage box") containing SDI ST 2110 gateways, JPEG XS servers and PTP-synchronized switches. A fiber-optic network was used to exchange signals between the two locations.

Measurements were taken at both locations for individual pieces of equipment, equipment groups and the setup as a whole over a period of two production days (8 hours each). The total energy consumption for one production day were measured at 71 kWh, corresponding to around 8.9 kW per hour of active production. Figure 3 shows the allocation of the values to the different production steps. 4.5 kW were attributed to the CER, which means that the components used to process the audio and video signals were responsible for half of the energy required. 2.2 kW of the remaining energy consumption were attributed to the control room, 1.2 kW to the cameras and 1 kW to the stage box at the event location.

The energy used by building technology such as air conditioning and heating was not measured and is therefore not included in the total energy consumption cited here. Furthermore, a large proportion of the equipment in the CER was operated 24/7. This setup is contrasted with conventional OB van productions with six to eight cameras. Measurements taken by us showed that the energy consumption for a comparable production are around 6–9 kW in this case, including the technology installed in the OB van, such as air conditioning and heating. The measurements therefore indicate that using a remote production setup cannot significantly reduce electrical energy consumption.

Remote production offers the crucial advantage that a large proportion of the production team (in the control room, for example) can work from a permanent central location. This significantly reduces the number of employees required at the event location, which cuts down on the CO_2 emissions involved in travel and accommodation. A setup of this kind also makes it possible for one production team to work on multiple productions in one day, rather than being limited

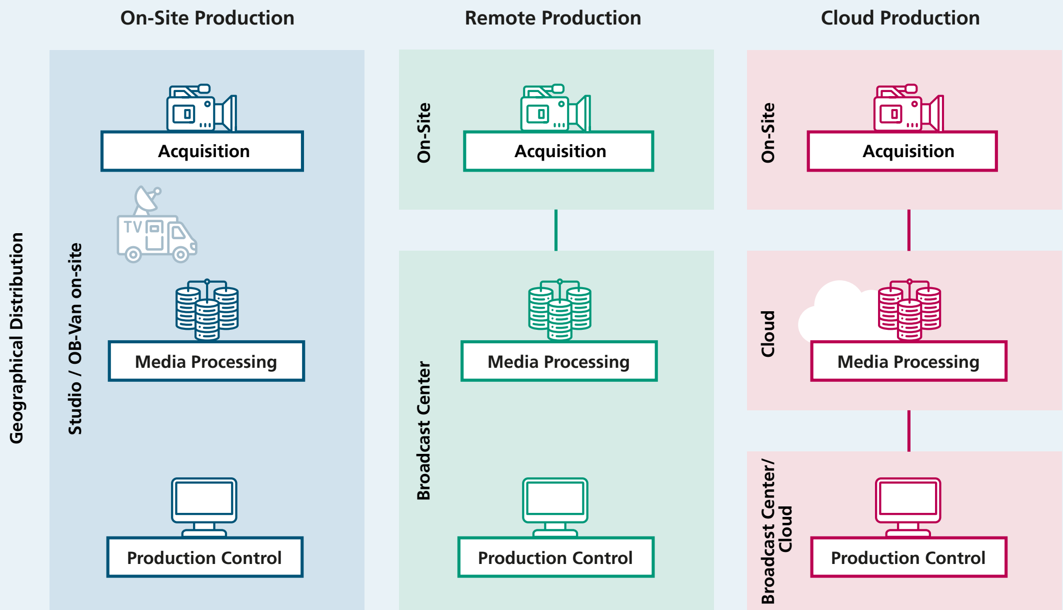
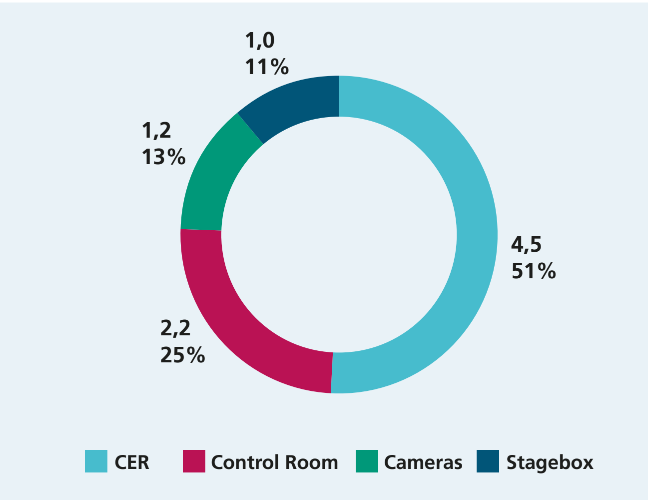


Figure 2: Types of Production

to one production due to their dependency on the location and availability of the OB van. Only essential personnel, such as the camera operator and lighting and sound technicians, still need to be present at the event location. Consequently, remote production offers considerable potential for reducing the emissions caused by travel and transport, using resources more efficiently and minimizing the need for board and lodgings for personnel. Viewed within the overall context, these emissions occur once per production and are not scaled with the number of viewers [7].

Figure 3: Average demand in kW



4.2 Ingest and encoding

Video encoding is an essential and central processing step when distributing video content via the internet. The data volume of video content is reduced by using video compression methods, also known as video codecs. This results in a compromise between the video quality and the data volume for the application in question. At the start of the value chain, camera signals are compressed slightly at first (contribution signal) to enable further processing in high quality. A higher degree of compression then takes place at the end of the streaming value chain to make the content suitable for various end devices and usage scenarios. This applies to conventional streaming and TV content as well as to the millions of videos shared on social media platforms every day. Efficient encoding solutions that conserve resources are therefore becoming more and more important.

Different approaches and architectures are used for this purpose depending on the application in question. The most widespread encoding solutions include adaptive bitrate encoding and content-aware encoding, which can in turn be implemented in hardware or software and as an on-premise or cloud solution. These solutions are also an example of how encoding methods can be combined together, with content-aware encoding used in adaptive bitrate encoding and vice versa.

As video codecs have evolved in order to preserve video quality while also reducing the data volume, the complexity of these codecs and the required computing power have increased, resulting in higher energy consumption for the video encoders. It is important to understand that video encoding and the compression methods that it uses constitute very specific

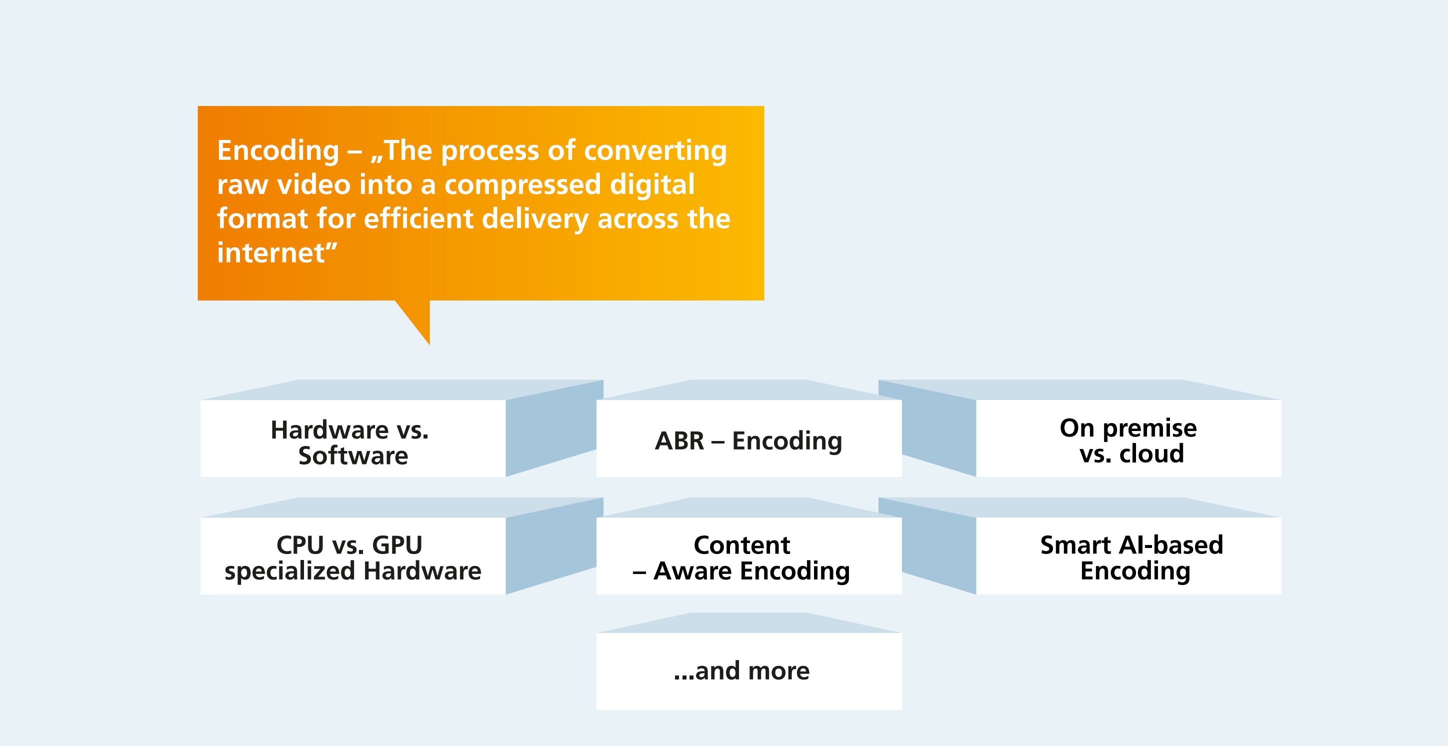


Figure 4: Encoding Strategies and Methods

computing tasks and can therefore be processed much more efficiently and with much fewer resources if specialized hardware is employed instead of conventional, versatile CPUs. GPUs (graphics processing units) are a typical example of this kind of hardware, and VPUs (video processing units) have recently started to enter the market too. They use highly specialized chips known as ASICs (application-specific integrated circuits) or FPGAs (field-programmable gate arrays), which are optimized for encoding with specific video codecs. In comparison with CPU encoding, this allows VPUs to achieve up to 50 times the data throughput and energy savings of up to 90 percent [8]. It also means that they surpass GPUs in terms of their efficiency.

These examples clearly show that the right choice of encoding solution can help to save a significant amount of energy. However, there is no one-size-fits-all solution. The best option in each case will depend on the streaming workflow, the end device to be addressed and the usage scenario (live event, video on demand, social media, etc.). All of these factors have an effect on the amount contributed by the encoding process to the total energy consumption of video streaming as a result of scaling effects.

4.3 Content delivery networks

Content delivery networks (CDNs) use energy-efficient hardware and software to minimize electrical energy consumption. Server virtualization and dynamic load balancing help to reduce the amount of energy required. A CDN must ensure that large volumes of data can be transmitted quickly and efficiently. The size of the CDNs and, hence, the required number of server nodes is planned on the basis of the peak-time demand — the maximum traffic peak to be expected for all services transmitted within a CDN.

CDN servers are operated 24/7. The peak load in the CDN occurs in the evening when lots of people are using video services (VOD, live). Figure 5 shows an example of the weekly electrical energy consumption of a CDN server as measured in the project. A striking feature of this graph is the high base-case electrical energy consumption of the server, measured at around 450 W. The peaks indicate an increase of around 50 W in the electrical energy consumption in the evening hours. As the project proceeds, a comprehensive analysis of the electrical energy consumption of a CDN will be carried out on the basis of real log data.

4.4 Distribution

Telecommunications networks are designed for peak loads, which results in inefficient excess capacity at quieter times. The majority of the networks' energy consumption still apply in the case of idle load and at quieter times. According to the network equipment provider Nokia, this accounts for around 70 percent of the total energy required [9].

Unlike end devices, which can quickly switch to energy-saving modes, load-adaptive operation of data centers and telecommunications technology requires a huge amount of technical effort. Providing computing power and network capacity without a delay presents a particular challenge for an automated energy management system.

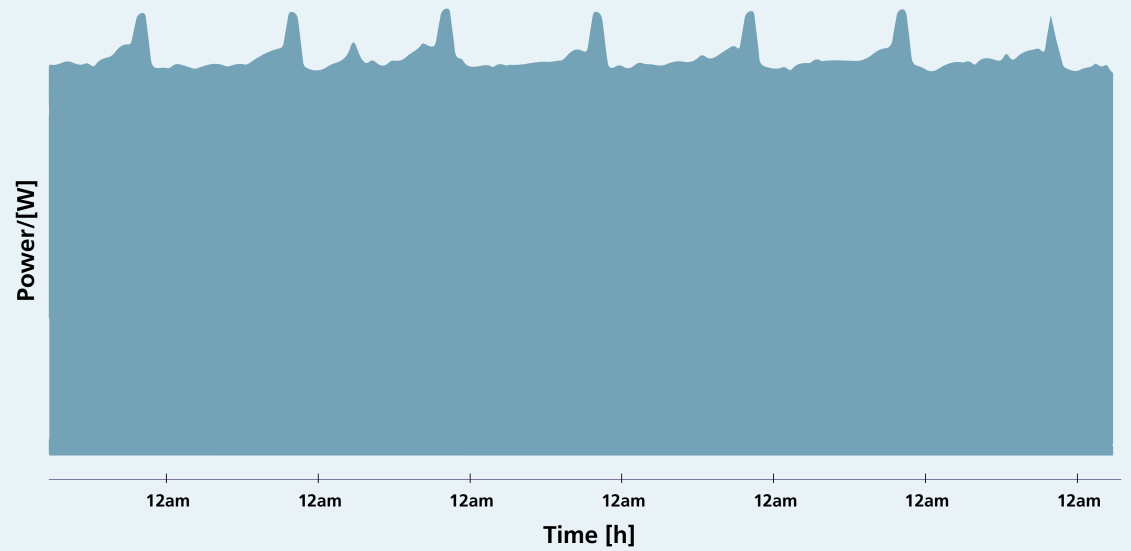


Figure 5: Typical Power Consumption of a CDN Server

Due to the large number of hardware components and the complexity of a telecommunications network, it is difficult to calculate the proportional energy consumption for video streaming. There are two main methods for modeling the energy consumption, as defined in 2.2.

The **energy intensity model** (EI model) is based on the volume of data transported through the network. The energy consumption are stated in kWh/GB or kWh/TB and are cited as a KPI in the ESG reports of many telecommunications providers as an energy efficiency value. This value gives an indication of the network's energy consumption and makes it possible to allocate emissions based on the volume of data consumed. However, this method is not suitable for a detailed analysis as it gives the impression that higher volumes of data lead directly to higher energy consumption in the network, which is not the case. A good estimate of the energy consumption for a core network, fixed network and mobile communications network based on the EI model can be found in [3].

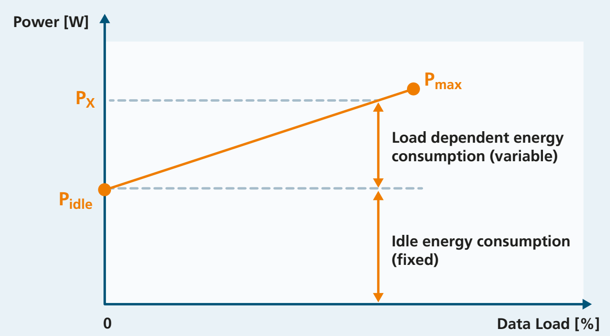
- Core network = 0.02 kWh/GB
- Fixed network = 0.07 kWh/GB
- Mobile communications network (RAN) = 0.2 kWh/GB

The **power model** [PM], on the other hand, also takes into account the fact that energy consumption are time-dependent. The basic assumption is that distribution networks still have relatively high energy consumption even when they are not transporting data (idle mode or base load). When data is transported, the energy consumption increase in proportion to the volume of data. The total amount of energy required is made up of a fixed value (idle energy consumption) and a variable consumption value.

The power model makes it possible to analyze short-term effects on the energy consumption when transmitting content to the end customer, as it is very good at representing the real conditions at the present time with regard to the available base load. It takes into account the complexity and characteristics of all components of the network.

The two models differ in terms of how they allocate the energy consumption of networks to the users — based on the transported volume of data alone or primarily based on time. The EI model should only be used for a retrospective analysis when the data transfer rate and total energy consumption are known. It can be used for the purposes of an annual efficiency analysis, for example. It is not suitable for calculating the

Figure 6: Modeling energy demand using the power model by Malmodin



current energy consumption of individual applications and services in the network, such as video streaming.

Neither of the models can be used to make statements about future electrical energy consumption resulting from changes to usage behavior, as changes to the network itself — for example, network expansion or transformation to fiber optics — will play a greater role in the future. This means that we need to define new models which take into account the technological progress in this area and the resulting user behavior. The following sections calculate and discuss the electrical energy consumption of various distribution networks on the basis of existing measurements and analyses.

4.4.1 Core network

Various estimates of the energy consumption can be found in the literature using the two main models (EI model, power model). The EI model values draw on a summarizing study by Coroama [3], while the power model figures are based on Malmodin's values [4].

4.4.2 Access network

The electrical energy consumption estimate for the access network from the sources cited above is presented in Table 2.

4.4.3 Broadcast

Although the popularity of video streaming content has been growing for years, around 95 percent of TV consumption in Germany in 2023 took place via the broadcast technologies of cable, satellite, antenna and IPTV [10].

An in-depth examination of the situation in Germany [11] indicates that the energy consumption of the individual broadcast technologies are all of a similar magnitude. In Germany, terrestrial antenna transmission (DVB-T2) has the highest electrical energy consumption of the four platforms at 10 Wh/h. This is due to the energy-intensive infrastructure comprising more than 150 transmitters, which is used less than in other countries. Terrestrial broadcasting accounted for just 6 percent in Germany in 2023 [10]. Satellite transmission, on the other hand, is very efficient as the satellites used in Germany reach hundreds of millions of households all over Europe and the signal uplink uses hardly any energy. As a result, the electrical energy consumption for the transmission is almost negligible (0.15 Wh/h). Meanwhile, the study cites a figure of 4–6 Wh/h for cable reception and 3 Wh/h for IPTV.

4.4.4 Comparison of different technologies

The energy consumption values shown in Figure 7 were calculated for the different access technologies with the aid of numerous sources. Comparing broadcast with streaming here would be inappropriate, as the DVB-T2 and satellite technologies are unidirectional service distribution mechanisms and cannot deliver a full and wide-ranging service offering.

Core Network (Core)		
Energy Intensity Model	**Power Model**	
	Fixed Network	Mobile (LTE)
0,02 kWh/GB	1,5 W +0,03 W/Mbps	0,2 W + 0,03 W/Mbps

Table 1: Calculation of Core Network Power Consumption

Access Network			
Energy Intensity Model		**Power Model**	
Fixed Network	Mobile (LTE)	Fixed Network	Mobile (LTE)
0,07 kWh/GB	0,2 kWh/GB	5 W+0,02 W/Mbps	1,0 W+1,5 W/Mbps

Table 2: Calculation of Access Network Power Consumption

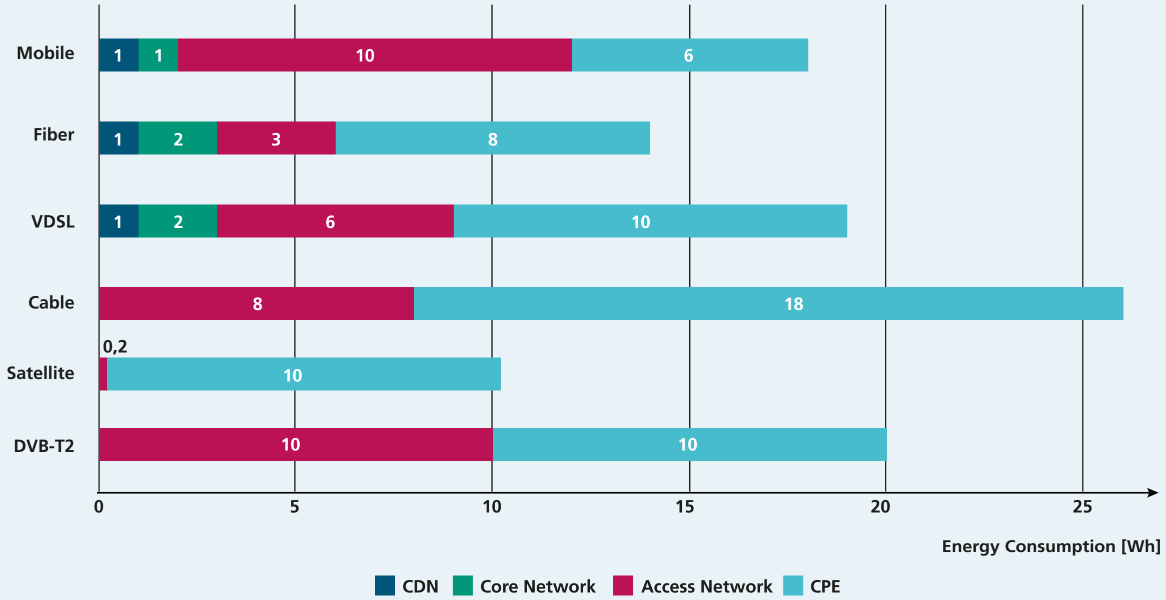


Figure 7: Power Consumption of different Distribution Technologies

The calculation was based on the following assumptions:

- The energy consumption in each case are stated for one hour of video streaming for a Full HD stream at 6 Mbit/s. In the case of broadcast (DVB-T2, satellite and cable), an HD TV channel at 6 Mbit/s — comparable with streaming — is assumed.
- The energy consumption are analyzed for each connection (line). This means that the total electrical energy consumption values stated for the network (e.g., DVB-T2) are based on the number of customers/households. The value for DVB-T2 therefore only applies to Germany [11].
- The electrical energy consumption is calculated from the point when it is fed into the grid until it reaches the reception equipment (tuner, router, modem, etc.). The end devices on which the content is viewed (smart TV, smartphone, PC, etc.) are not taken into account.
- The electrical energy consumption values for fixed networks and mobile communication networks are based on Malmodin's power model [4].
- Values for the CPEs are based in part on measurements taken in the project, manufacturer information and values from the JRC report [12]. The CPEs include amplifiers, such as those required for satellite reception.
- Mobile reception also includes a CPE (LTE or 5G router) which distributes the signal via WiFi. This reception scenario is also referred to as hybrid reception (combination of LTE/5G and DSL) and makes it possible to draw comparisons between the different connection options. The signal is generally received directly on a mobile end device.

Figure 7 shows that the differences in the electrical energy consumption of the networks and CPEs for video streaming are not huge. The most energy-efficient technologies are satellite for broadcasting and fiber optics for OTT streaming. The low energy consumption for satellite technology are due to the fact that energy is only required for the uplink. The satellite supplies itself with energy from solar modules while it is in orbit.

4.5 End devices

End devices are responsible for the majority of the energy consumption involved in video streaming. Even small potential savings add up to significant amounts due to the fact that they often apply to millions of users. It is therefore important to ensure we have an accurate understanding of the factors that influence the energy consumption of video streaming end devices and the extent to which they contribute to the total amount of energy required.

Our aim is to collect data that is as precise as possible by measuring the electrical energy consumption of video streaming end devices, to combine this data with metrics from the video players and to then use this as the basis for analyses. In order to validate the measurements and ensure that the results are verifiable, repeated measurements are to be carried out using a clearly defined test procedure. To this end, Green Streaming has developed a measurement framework which uses the Fraunhofer FOKUS FAMIUM Streaming Media Test Suite [14] to automate measurements on video streaming end devices, and then uses the FAMIUM Stream Analytics tool [15] to convert these measurements — together with the metrics obtained from the video players in parallel — into a shared and reliable database.

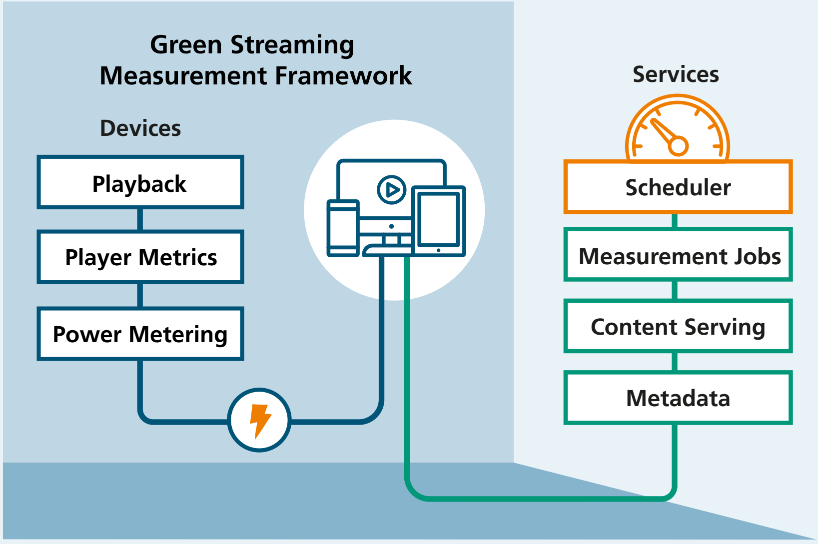


Figure 8: Green Streaming measurement approach

Numerous measurements were taken by playing a wide range of test content on different streaming end devices and measuring their power consumption and energy consumption. Smart TVs with different display technologies — from the categories of OLED, QLED, Direct LED and Edge LED — were selected with the aim of investigating the energy signatures of the different technologies for the selected test content. In addition to the direct measurements on the smart TVs, a streaming stick was used; this played content on the smart TVs via HDMI and was measured separately from the smart TV in question. The aim here was to reduce the smart TVs to their basic function as a display for further tests, thus eliminating the possible influence of other processing steps on receiving and decoding the content from the analysis. At the same time, the measurements for the streaming stick — which, with no display function, is almost exclusively responsible for receiving and decoding the content — provide a reference value for the energy required for precisely these signal processing activities. Measuring these activities on the smart TV itself would be subject to limitations.

The measurements reveal various energy signatures that are defined to a large extent by the display technology. OLED displays, for example, demonstrate a direct and comprehensible correlation between the amount of energy required and the brightness of the content being displayed. In the case of Direct LED and Edge LED displays, on the other hand, the power consumption remains virtually the same. The behavior of the OLED displays can be used to derive methods for energy-saving video streaming on end devices. Fraunhofer FOKUS has developed an appropriate solution in the form of FAMIUM GreenView [16]. This solution determines the optimum parameters for the specific content being played on the end device in question and reduces the display brightness such that energy can be saved while maintaining the perceptible image quality to the greatest possible extent.

Further measurements were able to demonstrate that the video bitrate in particular has no significant influence on the energy consumption of video streaming end devices. The differences between different resolutions in SD, HD and UHD with bitrates of 5 Mbit/s up to 25 Mbit/s are also marginal. In contrast to the brightness and display settings, there is no real potential for energy savings on the end device in this area.

The results also show that, in comparison with optimizing the streaming parameters, energy-saving modes on smart TVs (eco modes) are a highly efficient means of saving energy on end devices. It would be useful if viewers could be informed about the screen settings they are currently using and have energy-saving settings recommended to them from the streaming app or current TV show. The APIs required to do this are not yet available on today's smart TVs, or are only available to a very limited extent. With their help, streaming and TV providers would be able to adjust the relevant smart TV settings directly or display the options to viewers interactively. We would like to see a constructive exchange between researchers, streaming and TV providers, and device manufacturers in this area.

Figure 9: Correlation between brightness and power consumption of various Smart TV display technologies

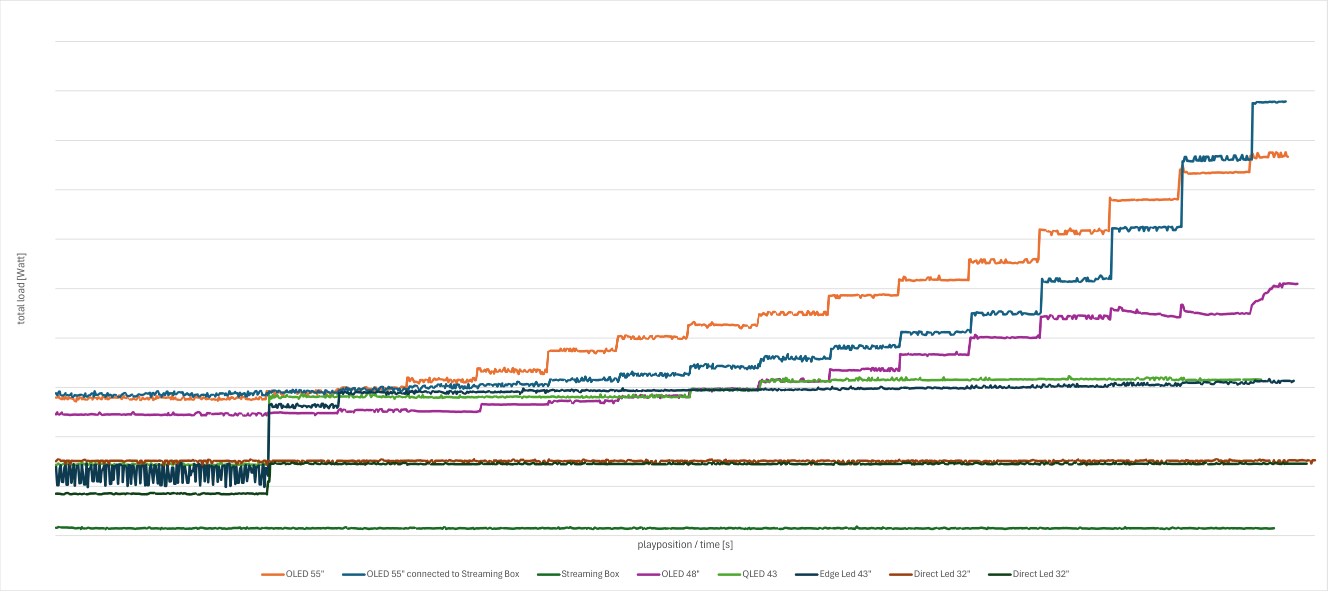
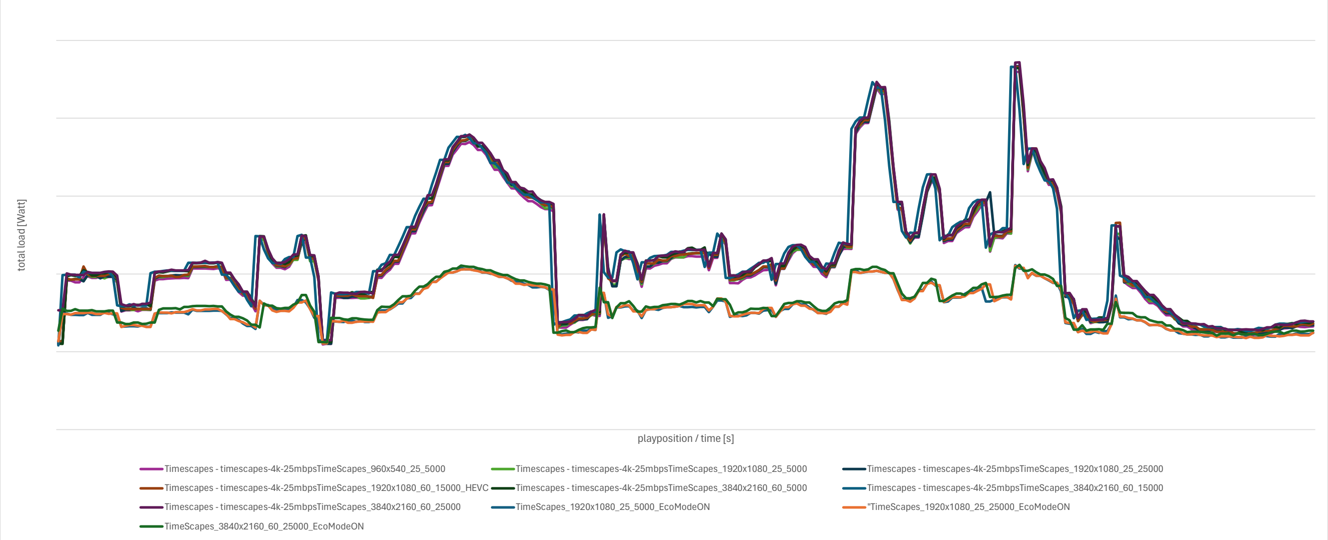


Figure 10: Power consumption of OLED TVs playing content at different bitrates and resolutions (with and without Eco-Mode)



5. Determining the carbon footprint of video streaming

Challenges involved in attributing emissions in the video streaming value chain and approaches for allocation and evaluation

When determining the carbon footprint of a company or product, various factors need to be taken into account: the relevance, monitoring and controllability of the emissions, the potential for mitigation as well as proportional data collection and transaction costs. The Green Streaming project is aiming to gain the best possible understanding of the carbon footprint of streaming applications based on the factors cited above. As detailed data is not currently available for all components of the streaming value chain, the electrical energy consumption values are calculated on the basis of models in order to identify the most important areas. Embodied emissions — i.e., emissions linked to the manufacture, transport and disposal of the products — are also taken into account here, drawing on values in the literature and manufacturer information.

5.1 Relevance of usage scenarios

Video streaming uses a shared infrastructure and, as with any matter of this nature, it is impossible to avoid the fundamental attribution problem — that is, how to handle the individual allocation of emissions. This is a sociopolitical and economic problem and will not be considered further within the context of the research project. We will be confining ourselves to the complex allocation of emissions based on viewers.

The number of viewers is a key factor in the allocation of emissions along the streaming value chain. Various idealized usage scenarios are being examined in order to estimate the energy consumption and CO_2 emissions for one hour of video streaming on one end device and to determine the influence of various parameters. The scenarios differ with regard to the number of viewers, the end devices used, the data rate in question and the transmission type (mobile communications or fixed network). It is assumed that all viewers behave in the same way regarding the data rate and end device. Details of the assumptions can be found in the appendix. This idealization makes it possible to investigate the influence of individual parameters and estimate the maximum and minimum energy consumption. The results reveal that the energy consumption of individual components respond to varying degrees to changes in the usage figures or usage behavior.

5.2 From electrical energy consumption and energy consumption to emissions

The electrical energy consumption and energy consumption of the various components of the streaming value chain are converted into CO_2e emissions. This is achieved by applying emission factors, which state the CO_2e emissions per kilowatt hour of electricity consumed from a given energy source. The emission factors also take into account the upstream chain; that is, the indirect emissions such as those connected with expanding the power grids, extracting fossil fuels or manufacturing solar panels, for example. These factors vary depending on the energy source and geographical region. Converting the figures provides a more effective way of evaluating the impact of streaming behavior on our climate and on sustainability in general.

5.3 Energy used to manufacture and dispose of hardware

A full emissions analysis takes into account not just the emissions generated during the use phase, but also those generated during manufacture, transport and disposal of the hardware. The embodied emissions of smartphones and smart TVs are known and can be estimated or taken from manufacturer information. On the other hand, the data for the manufacturing emissions in the first part of the streaming value chain — relating to outside broadcasting vans or cameras, for example — is often unknown. In such cases, we have used estimates where possible — for example, when evaluating servers, which we have not distinguished by specific configuration — or we have excluded the embodied emissions from the calculations following a rough relevance analysis, as in the case of the manufacturing emissions for the network.

5.4 Electricity requirements and emissions in the respective usage scenarios

The amount of energy required for one hour of video streaming on one end device depends to a large extent on the usage scenario. In this context, we will be looking at the influence of various parameters on the energy consumption and, hence, the emissions for one hour of video streaming. To turn the electrical energy consumption data into emissions, we use the emission factor for the German federal electricity mix, which takes into account the indirect emissions of the upstream chain for the electricity in connection with producing and transporting the electricity. The embodied emissions are determined on the basis of assumptions regarding the average daily usage duration and the service life of the devices. The emissions generated in connection with expanding the infrastructure are not considered here. Further details can be found in the appendix.

Table 3: Impact of the number of viewers on the energy consumption and emissions of one hour of video streaming on a single device

		Energy Consumption (Wh)		CO_2e-Emissions (g CO_2e)		Embodied Emissions (g CO_2e)
	Scenario	Power Model	EI Model	Power Model	EI Model	
Smart-TV	Football	170	431	76	192	115
	Local News	173	434	77	193	116
Smartphone	Football	18	666	8	297	5
	Local News	15	663	7	295	5

5.4.1 Influence of the number of viewers

Due to the scaling effects mentioned above, the number of viewers has a significant influence on the total emissions that can be allocated to a show or streaming provider — the more viewers, the higher the emissions. If, however, we look at the functional unit of one hour of streaming on one end device, the emissions that occur in the shared infrastructures at the start of the streaming value chain are allocated to the viewers.

We have assumed that the show will be streamed in HD. We have also assumed that the viewers using a smart TV are connected to the fixed network via a CPE, whereas the viewers using a smartphone are streaming directly via the mobile communications network. The scenarios in question are the UEFA European Championship with 10 million viewers, and a local news broadcast with 50 viewers. The energy consumption for one hour of video streaming on one end device are virtually the same for the two scenarios (viewed once on a smart TV and once on a smartphone). This means that the absolute energy consumption increase in an almost linear manner as the number of viewers grows.

5.4.2 Influence of the end device

The influence of the end device is examined on the basis of three cases: smartphone, smart TV and smart TV with HDR. Initial measurements indicate that smart TVs with HDR use significantly more electricity. For the purposes of this study, we have assumed a simplified value of 50 percent additional consumption. In the interests of comparability, we have assumed that all scenarios are streamed in UHD and that the data is transmitted via the fixed network.

Table 4: Impact of devices on the energy consumption and emissions of one hour of video streaming on a single device

		Energy Consumption (Wh)		CO_2e-Emissions (g CO_2e)		Embodied Emissions (g CO_2e)
	Scenario	**Power Model**	**EI Model**	**Power Model**	**EI Model**	
Smart-TV	UHD	169	791	75	352	115
	UHD HDR	243	866	109	385	115
Smartphone	UHD	21	643	10	286	6

The results reveal that the choice of end device has a considerable influence on the energy consumption and emissions. The chosen end device plays a particularly significant role when it comes to allocating the network consumption values based on the power model. From this perspective, the smart TV with HDR has 20 times the energy consumption compared to the smartphone. Due to the scaling effects, the energy consumption for the end device have a huge impact on the total emissions.

5.4.3 Influence of the data rate

This involves comparing video streaming in HD and UHD, each on various end devices: firstly on a smart TV with data transmission via fixed network, and secondly on a smartphone with data transmission via mobile communications network. In the interests of greater clarity, we are looking at the data rate here and have assumed for the sake of simplicity that the data rate is proportional to the resolution. The influence of the chosen resolution depends primarily on which model is used to allocate the energy consumption for network transmission.

When using the power model, the difference between the streams in HD and UHD is small. For the two scenarios, when viewed on a smart TV that is connected to the fixed network, the difference between HD and UHD is negligible. On a smartphone, with data transmission via a mobile communications network, the energy consumption double from 14 Wh to 28 Wh even with the power model, and hence the emissions double from 6 g to 12 g of CO_2e.

The energy intensity model provides a different interpretation. This model gives a much higher estimate for the energy consumption in each scenario. In particular, we can see a significant increase in the energy consumption when using the higher resolution — the amount of energy required increases by 80 percent in the case of the smart TV and more than doubles in the case of the smartphone.

When comparing the two models, it is not possible in this context to conclude that the lower resolution always goes hand in hand with significant energy savings. The amount of energy required by the network at the present time does not change greatly with the payload. For viewers who want to understand the emissions caused by their video streaming, the power model is more useful. However, for streaming providers looking to calculate their contribution to the annual emissions of the network as part of their sustainability reporting, the energy intensity model provides the correct perspective.

Table 5: Impact of datarate on the energy consumption and emissions of one hour of video streaming on a single device

		Energy Consumption (Wh)		CO_2e-Emissions (g CO_2e)		Embodied Emissions (g CO_2e)
	Scenario	Power Model	EI Model	Power Model	EI Model	
Smart-TV	HD	169	431	75	192	115
	UHD	169	791	75	352	115
Smartphone	HD	14	663	6	295	5
	UHD	28	1543	12	687	5

6. Conclusions and outlook

Industry and viewers share responsibility when it comes to sustainable video streaming

This white paper examines the core components of the streaming value chain with regard to their energy consumption and sets these requirements against the total amount of energy required for video streaming. The results reveal that end devices — subject to the scaling effects that occur due to content being viewed millions of times — contribute the largest share of the total energy consumption. The next largest share of the energy consumption in the streaming value chain is allocated to the networks. Live production infrastructure, encoding and packaging of content play a more minor role. As these processes are not subject to scaling effects, their energy consumption are relatively low.

Comparing the values for one hour of video streaming clearly shows that the EI model is not suitable for a time-based analysis over a period of an hour. This model is useful when it comes to reporting the energy consumption for longer periods; for example, over the course of a year. The power model is useful for comparing a wide range of influencing parameters such as data rate, network and end device.

Findings

- **Reducing the data rate** by means of efficient encoding methods does not significantly reduce the energy consumption of **end devices** such as streaming sticks, OTT set-top boxes and smart TVs.
- **The number of viewers** influences the allocation of emissions in shared infrastructures within the value chain, such as production, storage, ingest and encoding.
- **The calculated energy consumption** vary depending on the model used to analyze the network. When calculating the energy consumption proportionally for video streaming in the distribution phase (core and access network), it is important to take into account the fact that a large proportion of the energy consumption still apply even if no data is being transmitted (idle mode). This is factored in by the power model.
- **The electrical energy consumption is converted into CO_2 emissions** using emission factors which take into account the indirect emissions.
- **The energy consumption for manufacturing and disposing of the hardware** are taken into account in the form of embodied emissions in the emissions analysis.
- **Suitable hardware solutions and encoding strategies** can reduce the energy consumption for the encoding process and the downstream storage and distribution of content.
- **The display technology influences the electrical energy consumption** of the end devices and offers options for reducing the energy consumption.
- **Reducing the brightness or deactivating HDR** lowers the electrical energy consumption of the end device significantly.

Potential for reducing emissions

- **If viewers are given the right information, they can change their usage behavior — and thus make a significant contribution toward reducing emissions.** Individual settings such as screen brightness, display mode, activating energy-saving modes or adjusting the ambient

lighting can influence energy consumption. By choosing the most energy-efficient end device or the one best suited to the use in question, each individual viewer can make a difference.

- **Open discourse is required between market participants, researchers and end device manufacturers** so that the ideal device settings can be recommended to viewers via device APIs.

Outlook

The next steps in the project will focus on the automation and reproducibility of measurements, validation of the proposed methods and a transparent evaluation of the results. These steps are required in order to create a verifiable database, which will in turn be used as the basis for developing suitable tools (CO_2 calculator for video streaming) for the purposes of accounting and compulsory emissions reporting in accordance with the Corporate Sustainability Reporting Directive (CSRD [17]) including the Scope 3 emissions. By developing the CO_2 calculator for video streaming, the Green Streaming project is providing a tool which will help the relevant players in the media and streaming industry with a task that is set to become more and more important in future.

The current distribution networks are static and do not adapt to the specific requirements of the network, which means that network planning is based on peak loads. The consequence of expanding the network based on peak load measurements is that the energy consumption increase in the case of idle load. At the same time, measurements show that the peak load — at least with regard to the normal course of the day and disregarding situations such as large sporting events — is predictable. Furthermore, the rebound effect can be seen in distribution networks based on 5G technologies. 5G technologies promise to be more energy-efficient than 4G solutions, but this is counteracted by the increased use in terms of volume.

Making the distribution networks more dynamic could therefore save energy. How these more dynamic networks could be implemented is not included in our current scope of work, but would justify the cost and effort of further studies.

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8. Appendix

8.1 Usage scenarios

The usage scenarios examined here differ with regard to multiple parameters which are set out and explained below. The explanations also state the scenarios in which the relevant parameter is used and which assumptions have been made.

- **Number of viewers** determines the total emissions for video streaming. When considering emissions per hour of video streaming on one end device, the number of viewers determines the allocation of emissions at the start of the streaming value chain, particularly with regard to ingest and encoding.
  · Minimum value: 50
  · Average value: 100 thousand
  · Maximum value: 10 million

- **Resolution** determines the data volume and data rate transmitted during video streaming and thus influences the emissions in the network. We distinguish between the following options:
  · HD resolution: data rate 7 Mbit/s, data volume 3 GB
  · UHD resolution: data rate 16 Mbit/s, data volume 7 GB

- **Fixed network vs. mobile communications** determines the energy consumption of the network over the last mile. Transmitting data via the mobile communications network generally uses more energy than transmission via the fixed network. In most usage scenarios, we assume that the smartphone is connected via the mobile communications network, whereas the smart TV is connected via the fixed network. The values stated in 4.4 are used.

- **CDN:** For the relevance analysis, we use a flat-rate estimate of 0.5 W per viewer for the energy consumption in the CDN.

- **End device** determines the viewer's electricity requirements
  · Minimum value: smartphone, electricity requirements: 2 W
  · Maximum value: Smart TV, electricity requirements: 150 W
- **HDR** affects the electricity requirements of the smart TV. For the sake of simplicity, we assume that the HDR setting increases the electricity requirements by 50 percent.

- **Live transmission** is, in principle, outside the system boundary. However, we have indicated the energy consumption for live transmission for certain scenarios.
  · Minimum value: 7 W for 1 hour of live transmission from a smartphone
  · Maximum value: 80 kW for 1 hour of live transmission with 4 OB vans

8.2 Assumptions for Embodied Emissions

Device	Usage (h/d)	Lifespan (years)	Manufacturing emissions (kg CO_2e)	Manufacturing emissions per hour (kg CO_2e))	Source
Desktop PC with Screen	8	5	435	30	Gröger et al. Green Cloud Computing
Laptop	8	5	311	21	Gröger et al. Green Cloud Computing
Computer Screen	8	5	88	6	Gröger et al. Green Cloud Computing
Smart-TV	4	6	1000	114	Gröger et al. Green Cloud Computing
Tablet	1	4	200	137	Gröger et al. Green Cloud Computing
Smartphone	24	2.5	100	5	Gröger et al. Green Cloud Computing
Router	24	7	77	1	Gröger et al. Green Cloud Computing
Server	24	7	6700	109	Gröger et al. Green Cloud Computing
Projector	1	8	145	50	ADEME: https://base-emprein-te.ademe.fr/donnees/jeu-donnees, Video-projecteur
Decoder	?	?	60.9		ADEME: https://base-emprein-te.ademe.fr/donnees/jeu-donnees, Décodeur
Modem	24	7	82.9	1	ADEME: https://base-emprein-te.ademe.fr/donnees/jeu-donnees, Modem/fibre
Server	?	?	600		ADEME: https://base-emprein-te.ademe.fr/donnees/jeu-donnees, Serveur
Server	24	5	732	17	ADEME/NegaOctet: https://base-emprein-te.ademe.fr/documentation/base-impact?idDocument=167

Table 6: Assumptions about usage time, lifespan, and manufacturing emissions for various hardware to determine the embodied emissions per hour of usage

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