E2E-StreamCarbon: an end-to-end measurement framework for streaming emissions

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Abstract

Video streaming is a major contributor to global internet traffic and an increasingly significant driver of energy use in data centers and communication networks. However, estimates of its environmental impact vary widely due to differences in modeling assumptions and limited empirical measurements. This work proposes an end-to-end measurement framework for evaluating the energy consumption and assessing the carbon footprint of video streaming systems. It integrates measurements of server-side transcoding, network transmission, and client-side decoding to provide a transparent evaluation of energy consumption and associated CO_2 emissions. We experimentally evaluate the impact of video codecs (H.264, H.265, VP9, and AV1), video resolution levels, and adaptive bitrate streaming strategies on energy use and CO_2 emissions. Our results show that network transmission accounts for the largest share of emissions, while codec efficiency and adaptive streaming significantly affect the total system impact. To increase user awareness, we present a browser extension that visualizes estimated CO_2 emissions during YouTube video playback. Our prototype demonstrates how environmental information can be integrated into everyday digital services to support more sustainable media consumption.

Keywords

video streaming emissions, carbon footprint, energy measurements, video codecs, adaptive bitrate streaming

1. Introduction

Online video streaming has become a dominant form of digital media consumption. In 2023, platforms such as Netflix, YouTube, and Disney+ were estimated to account for over 60% of global Internet traffic [11]. While digital transformation has reshaped media consumption habits, it has also raised concerns, as streaming services consume substantial energy across devices, networks, and data centers, generating carbon emissions [6, 10]. However, estimates of energy usage and emissions from streaming media vary widely. Discrepancies stem from differing assumptions about device types, network efficiency, and electricity carbon intensity [6, 7] , highlighting the need for transparent methodologies that evaluate streaming across the full delivery pipeline. While most studies rely on high-level models or focus on individual components of the streaming pipeline, end-to-end measurements remain limited [9, 1].

In this research we adopt a measurement-oriented approach and evaluate energy consumption across the full delivery pipeline: server-side transcoding, network transmission, and client-side playback. We analyze how different codecs, video resolutions, and adaptive streaming strategies affect energy use and CO_2 emissions. In addition, we present a prototype user-facing tool that visualizes the estimated CO_2 emission of real-time video streaming[1]. The main contributions of this work are:

- A transparent methodology for end-to-end assessment of energy consumption and CO_2 emissions in video streaming systems.
- A browser-based visualization tool that estimates and displays the CO_2 impact of streaming configurations, potentially supporting more sustainable media consumption.

ICT4S 2026: The International Conference on ICT for Sustainability, June 08–12, 2026, Bern, Switzerland
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[1]Our browser extension allowing CO_2 visualization is available on: https://github.com/oteropaula/E2E-StreamCarbon

2. Measurement framework

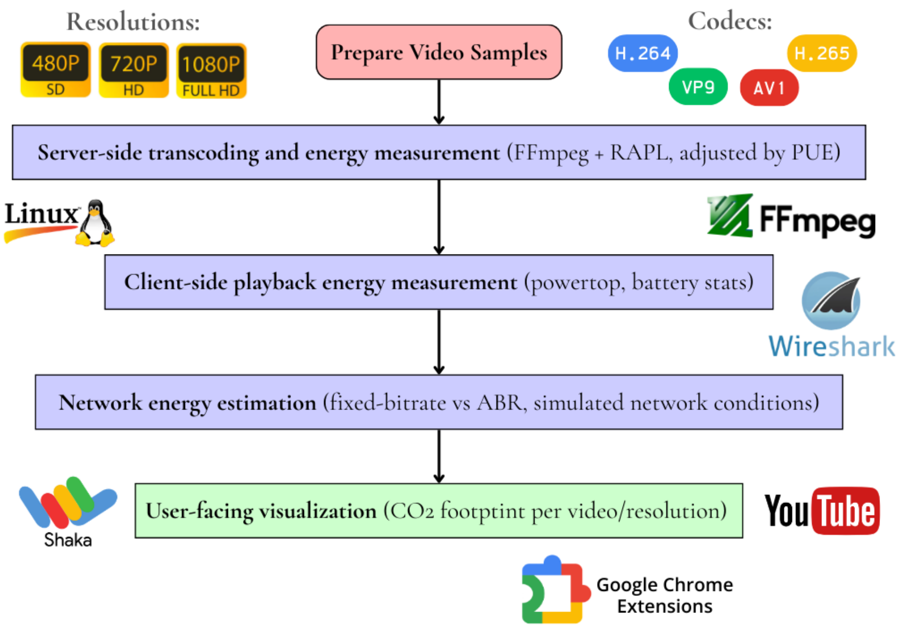

Figure 1: Holistic methodology for assessing energy consumption and CO_2 emissions of streaming video.

The proposed methodology (Figure 1), evaluates energy consumption of all main components of the video streaming pipeline: server-side video transcoding, network data transfer, and client-side decoding. We conduct experiments using Blender Foundation Sintel, Glass Half, Tears of Steal and Wing It open movies[2] encoded at 480p, 720p, and 1080p with four commonly-used codecs (H.264, H.265, VP9, and AV1). We obtain energy measurements using Intel RAPL tool [2] that provides fine-grain hardware-level CPU energy consumption readings and has been confirmed to correlate well with external power meters [8]. All experiments were conducted on a Lenovo ThinkPad X260 laptop running Linux with an Intel® Core™ i5-6200U CPU and 16 GB of RAM. Each measurement setup is repeated five times, and we report averages and standard deviation of the measurements.

We assess the following aspects of energy consumption:

1. **Server-side energy consumption** – evaluated by transcoding video files using FFmpeg, while recording processing time and CPU energy consumption through Intel RAPL counters.
2. **Client-side measurements** quantify the energy required to decode and play videos on end-user devices. We conduct playback experiments using the mpv player[3], with energy consumption estimated from RAPL readings taken before and after the playback.
3. **Network impact** is assessed by capturing network traffic during playback using Wireshark on a local Wi-Fi network. For adaptive bitrate (ABR) estimation, playback time was distributed across representative quality levels following a typical adaptive streaming model (30% at 1080p, 50% at 720p, 20% at 480p) [5].

To obtain CO_2 emissions, we apply emission factors to measured data volumes. More specifically, a network emission factor of 36 gCO_2/GB and server factors between 1–5 gCO_2/GB were adopted from official reports [6, 7]. Total emissions combine server-side transcoding, network data transfer, and client-side decoding contributions. Our study excludes device manufacturing, infrastructure construction, display energy consumption, and cooling overheads outside measured processing energy.

[2]https://studio.blender.org/films/
[3]mpv.io

3. Experimental results

3.1. Server-side encoding

Processing time and energy consumption both increase with resolution, reflecting higher computational costs associated with processing larger frames. **AV1 and H.264 achieve the lowest processing times**, VP9 requires substantially more computation across all video samples, while H.265 shows intermediate behavior. Energy consumption follows similar trends: codecs that require longer processing times also consume more energy. **VP9 consistently shows the highest encoding energy consumption**, followed by H.265, while H.264 and AV1 tend to be more efficient, with smaller variations in their relative efficiency across videos.

3.2. Client-side decoding

Client-side codec-related behavior differs from the server-side behavior. **VP9 and AV1 exhibit significantly lower decoding energy** during playback, with stable performance across different resolutions. On the other hand, H.264 shows higher energy consumption as resolution increases. **H.265 consistently requires the highest client-side decoding energy**, particularly at 1080p. These results demonstrate that the division of burden across the encoder and the decoder varies among codecs.

3.3. Network traffic

H.264 produces the largest file sizes and therefore the highest data transfer volumes. VP9 and AV1 achieve significantly better compression, producing files two to three times smaller than H.264. Our experiments further demonstrate that **Adaptive Bitrate (ABR) streaming substantially reduces network traffic** compared to fixed high-bitrate delivery by dynamically adjusting video quality.

3.4. CO_2 estimation

Combining network, server, and client measurements using Equation 1 shows that **network transmission is the dominant contributor to total emissions**. Server-side encoding contributes relatively little, while client-side energy depends mainly on playback resolution and codec efficiency.

$$\mathrm{CO}_{2,\mathrm{total}} = \mathrm{Data}_{\mathrm{GB}} \times (EF_{\mathrm{network}} + EF_{\mathrm{server}}) + \mathrm{CO}_{2,\mathrm{client}} \tag{1}$$

where $EF_{\mathrm{network}} = 36\mathrm{gCO}_2/\mathrm{GB}$, $EF_{\mathrm{server}} = 5\mathrm{gCO}_2/\mathrm{GB}$, and client-side emissions empirically measured.

4. CO_2 visualization tool

To make our results accessible to end users, we develop a browser extension that displays the estimated CO_2 footprint of YouTube videos directly within the platform. The extension estimates emissions based on two assumptions: an emission factor of 36 g CO_2 per GB streamed and standard bitrate estimates for each resolution. The current video resolution is detected through the HTML5 video element.

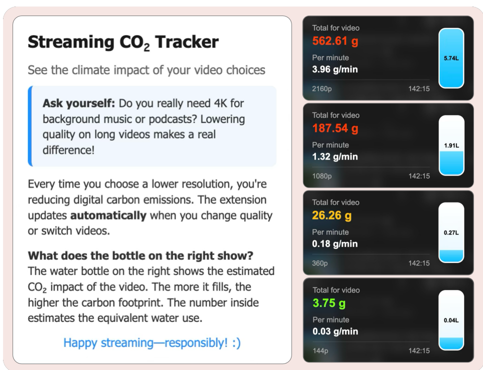

Figure 2: Browser extension.

The interface presents estimated emissions using a small overlay displaying total and per-minute CO_2 emissions. Color coding provides a quick visual indicator of environmental impact. For live streams, the interface displays the per-minute emission rate. (Figure 2). We also represent the impact by displaying the equivalent water consumption of video streaming, estimated from the energy intensity and water usage effectiveness (WUE) of both data centers and network transmission, while excluding client-side energy use due to device-specific variability. The calculation uses operational energy intensities of 0.055 kWh/GB for data centers and 0.059 kWh/GB for network transmission, together with corresponding WUE factors from prior work [3, 12, 4].

5. Relevance and novelty

Our results, fully presented on the accompanying poster, reveal key system-level insights into streaming emissions. Network transmission represents the dominant source of emissions in most scenarios, while client-side decoding becomes significant primarily at higher playback resolutions. Compression-efficient codecs, such as AV1 and VP9, reduce overall emissions despite higher encoding complexity by lowering the amount of data transferred over networks. Adaptive bitrate streaming further limits unnecessary traffic, indicating the importance of coordinated optimization across encoding, delivery, and playback. Beyond measurement, our CO_2 visualization prototype demonstrates how sustainability information can be integrated into digital services.

Acknowledgements: This work was partly funded by the Slovenian Research Agency project "approXimation for adaptable distributed artificial intelligence" (N2-0393).

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