Streaming the future of sustainability

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ABSTRACT

The rapid growth of digital video traffic presents both challenges and opportunities for sustainable content delivery. We argue that the shift towards on-demand streaming, exemplified by services like Netflix, provides a path to significantly reduce the carbon footprint and e-waste associated with traditional computing paradigms. By eliminating the need for local operating systems, enabling more efficient edge devices, and leveraging renewable-powered cloud infrastructure, streaming on-demand hardware and content can drive down energy use and embodied emissions. We analyze the key factors behind streaming's improved sustainability and chart a course for further optimization, envisioning a future where streaming is the default across all computing domains. This future will be enabled by a new class of streaming-optimized edge devices and continued innovation in areas like video coding, adaptive bitrate algorithms, and energy-efficient processing.

CCS CONCEPTS

• **Sustainability**; • **Ubiquitous and mobile computing**;

KEYWORDS

video streaming, sustainability, e-waste, edge computing, green cloud infrastructure

ACM Reference Format:
Ryan Hardesty Lewis and Alex Conway. 2024. Streaming the future of sustainability. In *Proceedings of 3rd Workshop on Sustainable Computer Systems (HotCarbon'24).* ACM, New York, NY, USA, 7 pages.

HotCarbon'24, July 9, 2024, Santa Cruz, CA

1 INTRODUCTION

Digital video was projected to grow 4-fold from 2017 to 2022 and account for 82% of all IP traffic [11], with estimates shooting up to 91% in 2024 with the emergence of short-form video platforms like TikTok [14]. Historically, the energy and material footprint of video distribution has been high, whether in the form of physical media like DVDs and the devices to play them, or in the embodied emissions of powerful user devices needed to decode compressed video [43]. The rise of on-demand streaming, made possible by the general increase in global internet speeds [12], offers a chance to bend this curve and deliver video more sustainably.

While previous research has highlighted the environmental impact of video streaming [25, 34, 37], we argue that a shift towards cloud-based streaming, including remote desktops and gaming, can actually improve sustainability. This builds upon the growing body of work demonstrating the potential for cloud computing to reduce carbon emissions through improved efficiency and the use of renewable energy [5, 24, 30, 41, 42]. Traditionally, studies have focused on the operational emissions of data centers, i.e., the emissions from powering the servers [6, 51]. However, this ignores the significant embodied emissions from manufacturing and transporting hardware, which can account for up to 50% of a data center's total carbon footprint [21]. We note, however, that the embodied carbon footprint of millions of deployed devices like smartphones, watches, and laptops far outweighs any cloud provider's current embodied carbon [18]. As cloud providers increasingly invest in renewable energy [49], the fraction of emissions coming from embodied sources in data centers is likely to grow.

We propose that by shifting computation and storage from local devices to the cloud, streaming can enable a more sustainable model. This allows for the consolidation of resources in energy-efficient, renewably-powered data centers, reducing both operational and embodied emissions. Furthermore, by intentionally limiting the hardware of edge devices to have a singular requirement of streaming, we can extend their lifetimes and reduce the need for frequent hardware upgrades, which can help mitigate the growing e-waste problem [17]. Phones, laptops, and other devices will not perform any computation and simply act as receiving nodes for computation that is performed using green energy somewhere else. In this case, we envision off-loading the entire operating system of the edge device to a remote server.

Streaming services like Netflix, Youtube and Amazon Prime Video have rapidly gained popularity, accounting for 70% of US internet traffic in peak evening hours [39]. With an advent of streaming remote hardware, like cloud gaming [8] and soon other intensive tasks such as remote desktops, we argue that this shift to streaming as the default video and computing method can significantly improve sustainability, by:

(1) Reducing e-waste and embodied emissions from physical media and associated playback devices
(2) Enabling edge devices optimized for energy-efficient video playback rather than general compute or storage
(3) Centralizing processing and distribution in cloud data centers powered by renewable energy

We quantify these benefits and chart a path for streaming to become the sustainable default for all content access across entertainment, education, work and personal computing.

2 REDUCED E-WASTE FROM PHYSICAL MEDIA

In 2021, CD, DVD and Blu-ray disc sales exceeded 1.2 billion units globally [35]. These discs become e-waste once the content is no longer wanted - over 55 million CDs are thrown away each year in the US alone [1]. Recycling rates are low, contributing to a significant accumulation of discs in landfills where they leach hazardous metals [53]. Streaming eliminates the need for this physical media, preventing megatons of e-waste [32]. Streaming also reduces e-waste from the devices used for physical media playback. DVD and Blu-ray players sold over 100 million units annually at peak [19], and even game consoles are primarily used for video playback [47]. With streaming, these transient devices can be eliminated in favor of single-purpose streaming edge devices. This allows resources to be pooled in the cloud for more efficient utilization.

The shift away from physical media like CDs and DVDs has been shown to significantly reduce e-waste and associated environmental impacts [32, 46, 54]. A similar transition is possible with computing devices. Currently, laptops and smartphones are treated as disposable, with an average lifespan of only 2-3 years [52]. This leads to a massive amount of e-waste, with 53.6 million metric tons generated globally in 2019 [17]. By moving computation and storage to the cloud, the need for frequent device upgrades can be reduced. Streaming enables a model where edge devices are primarily used for display and interaction, rather than intensive processing. This could extend device lifetimes, as performance demands would be less tied to local hardware capabilities.

Furthermore, with less need for local storage and processing power, devices could be designed with sustainability as a primary goal, prioritizing durability, repairability, and

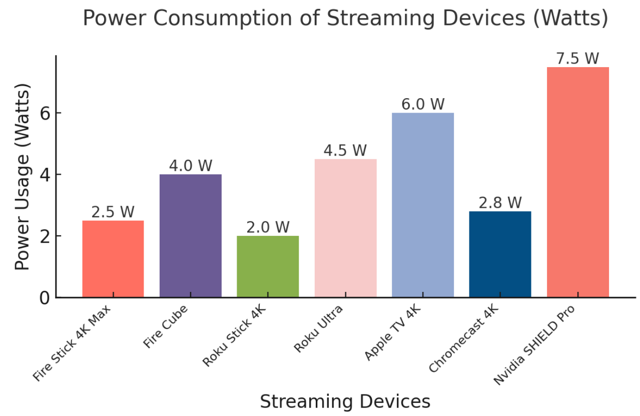

Figure 1: Relative power consumption of various streaming-dedicated hardware products.

modularity [10, 16]. This shift towards streaming-optimized edge devices, combined with the cloud-based model, could significantly reduce the environmental impact of personal computing, mimicking the benefits seen with the transition away from physical media.

3 EDGE DEVICES OPTIMIZED FOR VIDEO PLAYBACK

The computation needed for video decoding can account for 35-50% of playback energy usage on user devices [23, 28]. Since optimization of video codecs is a key priority for streaming providers [3], much of this computation can be offloaded to the cloud. This allows edge devices to be optimized for energy-efficient video decoding and display rather than general compute. We envision a new class of devices purpose-built and certified for low-power video streaming. These could forego local storage entirely in favor of cloud-synced content, and dedicate silicon area for hardware-accelerated video codecs rather than caches and out-of-order execution. Streaming sticks and dongles are a step in this direction, but a more radical rethinking is possible - e.g. screenless devices that wirelessly cast to displays. Such lightweight edge devices could have order-of-magnitude lower embodied emissions, since hardware is the dominant lifecycle energy cost [21]. They may also have longer usable lifetimes, since decoding requirements for a given resolution/bitrate will not change much over time, unlike the steady escalation of compute demands from apps and OSes.

To quantify the potential energy savings, we compare the power consumption of current streaming products. As shown in Fig. 1, different streaming devices exhibit varied levels of power usage, dependent on the streaming task. Selecting the appropriate device based on user needs can significantly impact energy consumption, emphasizing that energy-efficient options are available for lightweight streaming.

Table 1: Estimated carbon intensity of one hour of streaming.

Year	Carbon Intensity	Source
2019	394 g CO2e/hr	The Shift Project [48]
2020	55 g CO2e/hr	Netflix sponsored study [45]
2021	36 g CO2e/hr	International Energy Agency (IEA) [26]
2021	4 g CO2e/hr	France-Only Low-Carbon Sources (IEA) [26]

4 RENEWABLE-POWERED CLOUD INFRASTRUCTURE

By centralizing computer processing in the cloud, streaming providers can directly procure renewable energy for their data centers. While companies like Google and Facebook have committed to 100% renewable energy for their operations through purchasing offsets and renewable energy credits, it is important to note that their data centers do not run on 100% renewable energy at the point of use. [15] Likewise, Netflix has set a goal of net zero emissions by 2023 [33]. However, while not at 100% renewable energy, large cloud providers still operate on a higher sustainable energy usage than countries throughout the world, as large parts of Africa and Asia still rely on fossil fuels for more than 60% of their electricity production [38]. Large cloud providers can also site data centers in locations with abundant wind, solar, hydro or geothermal energy and invest directly in utility-scale renewable generation. Google has long-term agreements to buy 5.5 GW of renewable output [36]. Achieving this scale of renewable procurement would be infeasible with disseminated video processing on user devices.

Centralization also enables more efficient resource utilization and power proportionality. Netflix serves 200 million subscribers from around 100k servers [7], achieving far higher storage and compute density compared to individual user libraries. Advanced technologies like server and storage power management [27] can be used to dynamically scale capacity with demand, something impractical for user devices. Moreover, edge cloud offloading can alleviate the burden on centralized data centers by distributing computational tasks to nearby edge servers, reducing latency and bandwidth usage while maintaining energy efficiency [50]. Finally, placing servers near renewable generation opens the possibility of exploiting stranded power - energy that would otherwise be curtailed when supply exceeds transmission capacity or local demand [20]. Large tech companies are beginning to explore data centers as flexible load to absorb such power [13].

5 CARBON FOOTPRINT OF STREAMING

There are varying estimates of the carbon footprint of streaming video, as shown in Table 1. 2019 estimates from The Shift Project [48] put the emissions at 394 g CO2e per viewing hour, a correction to a prior study in which they had mistakenly claimed streaming video was equivalent to driving over 10 km [26]. However, the Shift Project's estimates are not considered reliable [26], with even a recent study sponsored by Netflix [45] estimating a footprint of just 55 g CO2e, 1/8th as much. The primary factors driving this low footprint are the technology trends described above - more efficient video codecs, the shift to cloud encoding from edge decoding, and the rapid adoption of renewable energy by cloud operators. The Netflix study finds that user devices still account for a large fraction (>50%) of overall energy usage in the streaming ecosystem. This suggests that major improvements are still possible, especially in reducing the environmental impact of devices. But even Netflix's footprint can be further reduced through the streaming optimized devices described earlier, as the International Energy Agency (IEA) finds that 55 g CO2e/hr is still far too high and a more realistic number is 36 g CO2e/hr, which they compare as similar to boiling a kettle at 35 g CO2/hr [26]. The IEA goes on to show that if streaming is done in countries where energy is low-carbon, such as France, then the carbon footprint is only 4g CO2e/hr, a figure that serves to show the potential future benefits worldwide of streaming from carbon-free energy in data centers and using low-carbon streaming devices.

Garmin estimates 6.4 billion devices in circulation in 2021 [4], with Precendence Research claiming a 5.1% compound increase in devices per year [2]. Using these facts in conjunction with the estimated cost of streaming to each device, we can forecast how many billion grams of CO2 streaming will cost. Figure 2 shows the estimates of carbon footprint over the 8-yr period, leading to 2 billion g CO2e annually saved if we compare Netflix's estimates to France's low-carbon streaming model. Due to this difference primarily in energy source [26], we posit that with improvements in device architecture to focus more on video streaming or a new class of streaming-only devices replacing traditional edge devices, carbon footprint can be brought even lower.

Our projections in Fig. 2 suggest a significant growth in the carbon footprint of streaming due to increased usage and improved streaming quality (e.g., higher resolutions). However, it is crucial to acknowledge that these projections are based on the assumption that streaming technology remains constant and that we will simply stream more. This assumption has been challenged in several prior works in ICT, which indicate that energy use does not scale linearly with data volume and that technological advancements often lead to greater energy efficiency [29, 31]. For example, Mytton et al. (2024) show that network energy use is not directly proportional to data volume, suggesting that future improvements in streaming efficiency could mitigate some of the projected increases in carbon footprint.

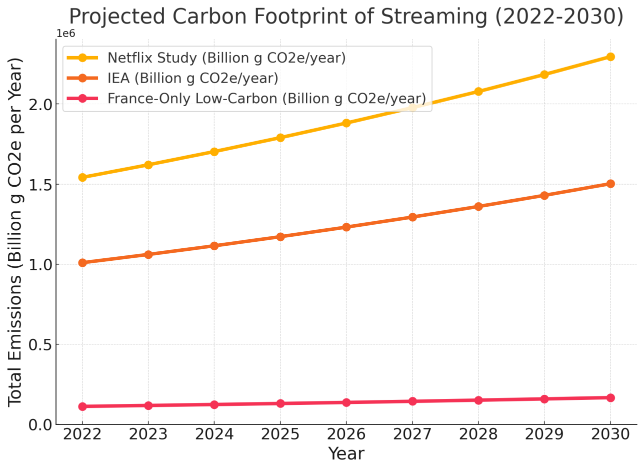

Figure 2: Projected carbon footprint of streaming video under current technological assumptions.[1]

6 TOWARDS PERVASIVE SUSTAINABLE STREAMING

In addition to the sustainability benefits, pervasive streaming offers a range of other advantages. By centralizing computation in the cloud, providers can dynamically scale hardware resources to match software demand, leading to more efficient utilization and reduced carbon intensity per workload [22]. This dynamic provisioning is challenging to achieve with edge devices that are inherently over-provisioned for their typical usage patterns. Streaming also enables users to access a greater variety of content and services without the constraints of local storage or processing power. For example, users could seamlessly switch between different operating systems or software environments on-demand, without the need for time-consuming local installation or configuration. This flexibility extends to the realm of gaming, where cloud gaming services like Xbox Cloud Gaming and Playstation Now allow users to instantly stream a catalog of titles without the need for dedicated gaming hardware. Eliminating local storage requirements also reduces the time and energy spent on downloading and updating content, as these tasks can be centralized and optimized in the cloud. The result is a faster, more responsive, and more energy-efficient user experience that adapts to the user's needs and preferences.

We believe that the convergence of efficient cloud infrastructure, renewable energy, and optimized edge devices can make streaming the most sustainable option for accessing video and all types of content. The key is to make on-demand retrieval from the cloud the default, rather than local processing and storage. This allows the burden of computation and decision making to be shifted to the cloud, where it can be done much more efficiently. There are still challenges to be overcome, both technical and cultural. Technically, streaming must be robust to varying network conditions and offer instant startup and interaction. Existing adaptive bitrate techniques [44] and AI-based video compression [55] provide a path forward here. Achieving fully cloud-offload playback may require co-design of new device hardware and software video formats - an area ripe for research. Culturally, users will need to embrace the idea of accessing all content and even processing on-demand, rather than "owning" the hardware or content their devices are streaming. The success of music streaming points the way, but video remains more challenging due to its sheer scale. While display resolutions are increasing to 8K and beyond, advances in disk capacities have also kept pace, making it feasible to store high-resolution content locally. However, the convenience and efficiency of streaming, particularly in terms of reducing e-waste and operational emissions through locating where heavy computation is performed, still present compelling advantages. Economic models like micropayments per view rather than all-you-can-eat subscriptions may help manage the cost [9].

7 SCOPE AND LIMITATIONS

Our analysis focuses primarily on the potential sustainability benefits of streaming for digital video and mobile computing workloads. We consider scenarios where edge devices are over-provisioned for these workloads, leading to unnecessary embodied carbon and e-waste. The estimates of carbon savings are based on available data and reasonable assumptions about device lifetimes, usage patterns, and the carbon intensity of manufacturing and electricity production.

However, we acknowledge that streaming is not a one-size-fits-all solution and may not always be the most carbon-efficient approach. The embodied carbon of network infrastructure and the energy consumption of data transmission can offset some of the benefits of reduced local processing and storage. In general, performing computation on a remote server with low-carbon energy will always be better for the environment than running on dirty energy, but streaming may also be less suitable for latency-sensitive applications or situations where network connectivity is limited. These issues are being rapidly addressed by the deployment of blanket coverage from satellite internet services such as Starlink and their general improvement in speeds. Furthermore, our analysis relies on estimates and assumptions that may not capture the full complexity of device lifecycles and supply chains. More comprehensive lifecycle assessment studies are

[1]These heuristic projections should be interpreted with caution, as they do not account for potential improvements in streaming efficiency and other technological advancements, according to Mytton et al.

needed to quantify the net environmental impact of streaming in different contexts and how much longer a device for streaming will last compared to one created for general use.

It also may be the case that devices should only stream part of their activities, such as how video-streaming services have augmented away the downloading of videos. Only intensive tasks, like gaming or heavy computation, may be streamed with lower-level tasks being done locally.

We also acknowledge the long-standing debate between thin and fat clients, which has been a topic of discussion in the computing community. Thin clients rely on servers to perform the bulk of the processing, while fat clients handle most tasks locally. Our paper argues for thin clients from a sustainability perspective, specifically focusing on the reduction of embodied carbon. Thin clients, with minimal hardware requirements, can reduce e-waste and extend device lifespans. However, this approach is not without controversy. Users value the capabilities of modern smartphones and tablets, including on-device processing power for various applications, which thin clients may lack, but can be solved instantly with streaming. Satyanarayanan et al. (2009) argued for similar mobile offloading to nearby fat clients [40], which can finally be realized by blanketed networks of today and the possibility for no device to be disconnected from the Internet.

Finally, the increased reliance on cloud services for streaming raises important questions about security, privacy, and user control over data and devices. While there are potential benefits in terms of sustainability, these must be weighed against the risks and challenges of a more centralized computing model. Despite these limitations, we believe that our analysis provides a useful starting point for exploring the potential of streaming as a sustainable computing paradigm. By identifying key opportunities and challenges, we hope to motivate further research and development in this area.

8 CONCLUSION

This position paper argues for streaming as a future domain default for computing. Edge devices will effectively have no resources stranded and be fully utilized for their singular purpose of streaming. For example, a user reading this paper online in the future should do so from a streamed viewer, with no computation done locally to process where the text should be located next. Instead, a hardware-optimized streaming-only device receives the video stream from a local cloud, making their device effectively last forever with low operational and embodied carbon as all computation is done remotely where it can use sustainable energy. We show throughout this paper how the streaming model, and the cost of communication via networked nodes, have been driven low enough in recent years for sustainable streaming to be a feasible solution and even recommended for high-carbon energy consuming countries. We acknowledge the trade-offs with this approach, as higher bandwidth might be consumed to stream a document rather than download it, but propose a future where network communication is essentially given for free and at-scale via satellites and towers, making purpose-built streaming edge devices more sustainable and energy dynamic compared to a fixed operational carbon on-device.

Streaming video has already achieved remarkable sustainability gains compared to previous distribution methods. By making streaming the default for all content access, further reductions in emissions and e-waste are possible. Purpose-built streaming devices, renewable-powered cloud infrastructure, and a cultural shift to on-demand access all have a role to play. With the right technical and policy incentives, streaming can lead to a far more sustainable model of pervasive computing. The key open problems we identify are:

- Defining a reference architecture and benchmarks for ultra-low-power video streaming devices
- Reducing the carbon footprint of cloud video processing through workload optimization and hardware / software co-design
- Improving video codecs and adaptive streaming algorithms for the highly variable networks typical of mobile devices
- Incentive structures and economic models to encourage a rapid switchover to streaming across all media types

In future work, we plan to prototype streaming-optimized devices and evaluate their energy/carbon footprint compared to current general-purpose devices. We are also building an end-to-end general streaming platform and ecosystem to benchmark and quantify the highest leverage points for sustainability gains across both different host and receiver devices. By addressing these challenges, we hope to make pervasively sustainable streaming a reality.

ACKNOWLEDGMENTS

The authors thank Netflix for sharing the results and methodology behind their recent carbon footprint study, as well as Udit Gupta for their feedback and guidance.

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