Calculating the Carbon Footprint of Streaming Media: Beyond the Myth of Efficiency

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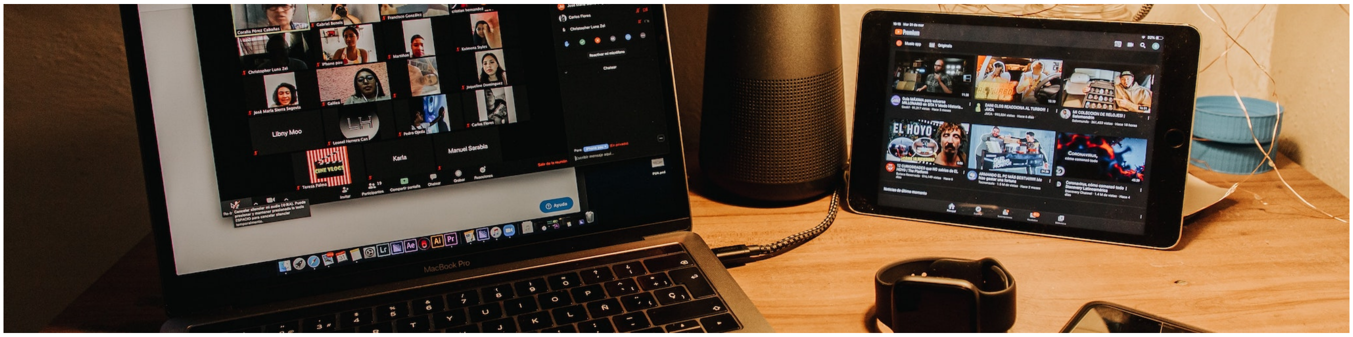

Figure 1: The many ways to stream media. Photograph by Gabriel Benois on Unsplash

ABSTRACT

What is the carbon footprint of streaming media? This has become a hot topic and more relevant question since the start of the COVID-19 pandemic and the need for self-isolation. What is needed is a reasonable model that considers all previous models published within the literature. However, whereas the existing models are either too high-level or incomplete and partial, we propose a holistic end-to-end model that balances the high-level and highly detailed. Additionally, most current models push a political agenda that biases the resulting calculations. We have taken a more neutral approach to avoid possible underlying motives or bias. We work our model by calculating the environmental impact of watching one hour of Netflix and showing the carbon footprint of a stream and the impact of unused energy in data centers.

CCS CONCEPTS

• **Applied computing** → Media arts; • **Networks** → Public Internet; • **Social and professional topics** → **Sustainability**; • **Hardware** → **Impact on the environment**; • **Human-centered computing** → **Ubiquitous and mobile devices**.

KEYWORDS

carbon footprint, communications network, consumer devices, ICT, internet, streaming media, telecom, video

1 INTRODUCTION

The energy consumption of *information and communications technology* (ICT) is increasing, both absolutely and as a proportion of global energy consumption. Estimates vary widely. However, since fossil fuels account for 80% of energy worldwide (World Bank 2015), ICT's energy consumption translates directly to a significant and rising carbon footprint. With the advent of the COVID-19 pandemic and the world-wide initiatives in many countries to self-isolate, the video streaming demand has skyrocketed, with the BBC reporting an increase of 71% [56].

The most significant driver of this increase is streaming video files (Cisco 2020). This is due to the large file size of videos and the fact that billions of videos stream worldwide—though mostly in wealthy and well-infrastructured regions—every hour. Streaming video includes video-on-demand platforms, consumer-upload platforms such as YouTube and Vimeo, video embedded in websites and social media, video chat applications (e.g., FaceTime), video conferencing, and online games. Streaming media exemplifies the substitution effect of ICT, where other types of products are replaced by their digital equivalents [51]. It may be the clearest example of the rebound effect, as increased efficiency results in higher bandwidth and, as a result, higher consumption.

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The wild-card variables in the expansion of ICT's carbon footprint are applications dependent on machine learning or artificial intelligence, cryptocurrency, and some Internet-of-things applications, such as self-driving cars. These applications depend on energy-intensive graphics processing units (GPUs). Though only 5% of servers shipped globally in 2016 had GPUs, Shehabi and colleagues include a GPU scaling factor in their calculations of data center energy intensity ([59]; for a survey of GPU energy intensity see [14]).

Cryptocurrency mining has a massive carbon footprint. The Bitcoin Energy Consumption Index published by Cryptocurrency blog Digiconomist [16] estimates that the annualized carbon footprint of Bitcoin is 114.06 Mt CO2, equivalent to the carbon footprint of Czechia, while Bitcoin's annual power consumption is 204.50 TWh, comparable to that of Thailand. Proof-of-stake is a transaction verification system proposed as a more energy-efficient method to the proof-of-work consensus method because it is the coin owners and not miners that create blocks, and thus dispensing with the need for power-hungry, CO2-emitting processing machines [16]. Similarly, self-driving cars generate vast quantity of data and thus necessitate massive bandwidth. As Lange and Santarius [33] point out, their data volume amounts to 4,000 GB per car per day. Massar et al. [43] argue that while autonomous vehicles can contribute to reducing GHG emissions by 35%, which is mostly due to eco-driving and platooning, faster travel can contribute to increasing GHC emissions by 41.24%. These energy costs, on top of streaming video at increasingly high resolution, will drive ICT's carbon footprint to new high levels.

Unlike streaming video, these applications are not ubiquitous now, but their use is expanding rapidly. Therefore, it is crucial that engineering research in sustainable ICT reach and educate a larger public. ICT engineers' calculations of the energy consumption and carbon footprint of ICT as a whole, and streaming video within it, differ, as do their proposed solutions. However, we believe there is enough consensus among ICT engineers on this pressing environmental issue that the broader public would pay attention to an alarm sounded by the engineering community.

2 GENERAL BACKGROUND

Our study [34] examines how methods to calculate the electricity consumption and resulting carbon footprint of ICT as a whole, and streaming media in particular, have changed over the last several years. We review almost 200 articles: about 125 in engineering, 20 in social sciences, 18 industry white papers, and 25 media reports. We survey 22 studies of the electricity consumption of ICT. There we find enormous variation in the ICT engineering literature regarding the relative contribution of data centers, networks, and devices to the electricity consumption of ICT, given a life cycle analysis; reliability of data; reliability of mathematical modeling; projected energy efficiency. We found that some engineers have overestimated the environmental impact of ICT, both current and projections. Others, often quite influentially, underestimate ICT's current and projected environmental impact. (For example, Masanet et al.'s 2011 article [42] assuring that the energy consumption of data centers has reached a plateau has been cited 108 times. Masanet also publishes reassuring articles for general readers, meanwhile advocating government subsidies for ICT, such as [41].) Others take a moderate view. We review eight studies of the electricity consumption of streaming media, drawing attention to variations in the definition of system boundary. At the broadest, the system boundary for streaming media includes production energy, which is especially significant for devices, as 85–90% of their lifetime energy consumption is calculated to occur in production; as well as, for a full life-cycle analysis, raw-material extraction, water consumption, disposal, and environmental toxicity [23, 48].

Surveying comparisons of the environmental impact of streaming with watching DVDs, we learn that streaming one video does consume less electricity than driving to the video store to rent a DVD. However, over the course of about a decade, the availability of online video created new consumption patterns. Shehabi et al. [61] assumed that a consumer watches only five hours of movies per month. But now many people stream that many hours of video content, on multiple platforms, per day. Nair et al. [48] calculate that the global warming potential (GHG emissions plus environmental toxicity) breaks even when four times as many movies are streamed as watched on DVD. At the time of their study, 2017, U.S. consumers were viewing eight times more movies then when physical distribution dominated. Therefore new streaming habits, driven by addictive design, not only canceled out any energy savings but also, in classic rebound effect, are using more energy.

By triangulating with eight different calculations of the energy consumption of streaming media, together with a Fermi calculation (i.e., back of the envelope), we can confirm the assessment of French think tank The Shift Project [44] — despite its use of the additive method — that streaming media was responsible for about 1% of global greenhouse gas emissions as of 2019. That figure is increasing quickly and contributing to the expansion of ICT's overall energy footprint [2, 6, 53].

We then analyze an attack by a spokesperson for the International Energy Agency on the streaming carbon footprint calculator developed by The Shift Project. We study debates about the energy efficiency of ICT and the end of Moore's Law and Koomey's Law. We conclude the report with a survey of recommendations to mitigate the carbon footprint of streaming video, highlighting those we find most promising, at individual, industry, federal, and international levels.

Elsewhere we examine the rebound effects of streaming media; critically examine debates over energy efficiency and the ends of Moore's Law and Koomey's Law — which, given their coming demise, would better have been termed trends than laws; critique the exporting of unsustainable ICT consumption in wealthy countries to developing countries; and explore ways that small-file media can be both sustainable and satisfying [39, 40].

Recently a consensus has developed that it is not feasible to separately parse out the contribution of streaming video to ICT, except for large contributors like YouTube [54]. Power consumption of data centers, networks, and devices must be measured separately (e.g., [2, 22]). Some engineers (e.g., [37]) argue that more data, as in streaming video and other data-intensive practices, does not necessarily result in more energy consumption. This is because networks and data centers are running 24/7, regardless of data use. As Chris Preist says, "With current network technologies, if you send less data along it, in most cases it doesn't reduce the energy use. It's like an airplane: if you don't fly, the plane flies anyway, and so 'not flying' only reduces emissions if it leads to less airplanes flying in the long term" [8].

Preist and colleagues [54] point out that reducing data flow results in less energy use only if the reduction is significant enough to make the cellular network use less energy, for example powering mobile cells down when demand is low, or using adaptive antennas. They also warn of rebound effects, such as that using less electricity for YouTube would make room in users' data plans for other streaming. Other authors debate that network efficiency translates to decreased energy consumption. "The overall infrastructure is growing too fast for the efficiency gains to offset this growth, and there is currently an unsustainable absolute growth in energy consumption" [53]. As we point out in this article, increased demand for streaming and other data- and calculation-intensive applications such as AI and cryptocurrency result in infrastructure expansion: not only of individual operators but of the number of operators as a whole. An individual consumer uses several different streaming platforms, often in the course of a single day; e.g., YouTube, Netflix, Hulu, videoconferencing platforms, social media platforms, chat platforms, gaming platforms, institutional intranets — all of which require separate infrastructure. This layering of infrastructure can be analyzed by compiling the electricity consumption of data centers and networks operated by separate telecoms and platforms.

To follow up the metaphor, increased demand, including the construction of new streaming platforms by competing companies, is leading to new fleets of airplanes being built. The US Energy Information Administration [1] projects a 28% increase in world energy use by 2050, mostly outside the OECD, as populations and incomes rise. Almost every kind of energy consumption will rise: renewable, nuclear, natural gas, petroleum. Renewables will support only the increase in demand; fossil fuels will maintain at a steady state. Corporations such as Apple and Google claim that their data centers are sustainable because they are powered by renewable energy. In fact, data center operators purchase renewable energy credits, which gives them the right to claim they are using renewable energy, while continuing to use energy from fossil fuels [9]. Moreover, that renewable energy could have been used to power the local grid. Thus even if new electricity generation for data centers, networks, and devices comes from renewable sources, this is in addition to, not replacing, the existing fossil-fuel-powered electricity sources.

3 EFFICIENCY: DOING MORE WITH MORE

Efficiency is demonstrated by the ratio "useful output per input." The efficiency of computing has increased impressively since the first mainframe computers. However, in an illustration of the Jevons paradox, ICT's consumption of energy and material resources has increased even more. Data centres, networks, and devices are ever more efficient, but the work they are required to do increases even faster, resulting in ever greater consumption of electricity.

According to Koomey's Law, the peak-output efficiency of computing hardware doubles every 1.57 years [29]. Since data centers only work at peak output 10% of the time [29], this might not seem to be a pressing concern. Yet Koomey's Law is reaching an end too [30]. Koomey and Naffziger's article [30], reassuringly titled "Moore's Law Might Be Slowing Down, But Not Energy Efficiency," originally bore the gloomier title "Efficiency's Brief Reprieve." Energy efficiency is the capacity to do more with less energy, and the ICT industry is working overtime to make all system elements more efficient. Unfortunately, the goal is not that data centres, networks, and devices do the same amount of labor for less energy, but that they can do more labor, in response to accelerating demand, for the same amount of energy.

Similarly, Shehabi and colleagues warn that "the recent stability in electricity demand may be a limited phenomenon" [60]. As the most efficient data centers come to predominate in the United States, known potentials for efficiency are becoming exhausted. They predict that electricity use will rise. Past models of FPE growth may be eclipsed by the Internet of things economy and increasing use of GPUs for artificial intelligence, to support things like autonomous vehicles. The fact that Moore's Law is slowing down, for which the authors cite numerous references, also presages the end of efficiency: global data center electricity use could double by 2030 (they cite [31], [21] corroborates this analysis).

The pessimistic tone of this article makes it even more surprising that Koomey and Naffziger [30] put such a cheerful face on energy efficiency in their public-facing article.

In part this coming spike in data center electricity use is because transistors are reaching physical (not theoretical) limits. The well-known Moore's Law, according to which the number of circuits on a chip doubles every 2 years, is slowing down. Moore's Law is explained by the phenomenon known as Dennard scaling [7, 26, 29].

Data- and computation-heavy applications—mobile computing, broadband and digital wireless telecommunication, handheld music players and GPS devices, smartphones, download services, video streaming, Internet shopping, social networks—are enabled by CMOS Very Large Scale Integration (VLSI) circuits, which integrate millions of logic gates on a single silicon microchip [26]. For decades metal-oxide semiconductors have been the workhorses of ICT. In Dennard scaling, the geometric shrinking of a metal-oxide semiconductor is accompanied by a proportional decrease of the supply voltage. However, as the supply voltage decreases, it reaches the threshold voltage at which circuits begin to leak electrons exponentially. Dennard scaling came to an end in 2004 [26]. When Moore's Law will come to an end is a matter of debate [22].

As in other articles, [60] place hopes on emergent forms of computing that would be immune to Moore's Law, such as quantum computing. Assurances that the energy demand of ICT can be managed through energy efficiency, renewable energy, and improved cooling of data centers is maintained by the International Energy Agency [27] and the more sanguine engineers like [41, 63]. However, such efficiencies may well be outweighed by corporations' determination to grow their markets [50].

Energy efficiency, then, is the ICT sector's defensive response to demands by telecoms and video streaming services (and AI and cryptocurrency) to underwrite the cost of their energy-hungry products.

Conversely, some engineers accept that a contraction in demand is the only solution to the spike in ICT electricity consumption. It is worth quoting Kaeslin at length. "While it is utterly clear that there can be no further progress without corresponding improvements in energy efficiency, the thirst for ever higher data bandwidths, the quest for better video resolutions, the current move towards storing everything in the cloud rather than locally, the desire to communicate even with humble objects over the Internet, and similar trends will in all likelihood continue to drive up the energy demand of ICT as a whole. Unfortunately, CMOS scaling alone can no longer be counted upon to yield the same gains in terms of performance, efficiency, and cost reduction as in the past. And unless a radical breakthrough occurs, growing capital needs will further restrict the number of manufacturers in the semiconductor industry" [26].

Sociologist-engineer team [47] make the unpopular point that "the very idea to limit data demand, in any form, goes against the dominant paradigm in which digital services and government policies, alike, are designed" [p. 136]. They criticize a 2017 policy goal announced by the UK's Department for Digital, Culture, Media & Sport that 95% of UK households should have ultra fast Internet of over 24 Mbps by 2020. After [12], Morley and colleagues call policies like this "invisible energy policies" (136), as they take no account of the energy demand and resulting carbon emissions of universal high-speed Internet.

Costenaro and Duer remark that because most of the electricity consumption is invisible to consumers, consumers remain blissfully unaware of their streaming energy footprint: a situation that has not changed much in the 10 years since they published this. "This creates a societal 'tragedy of the commons,' where end users have little incentive to consider the other 62% of costs and associated resources" [11] (pp.13-65). Referring to the energy efficiencies described by Moore's and Koomey's Laws, they ask, "Is this a license, however, to do as much computation as we want? To use the Internet without regard?" Similarly, as DeDecker [15] of the solar-powered website Low-Tech Magazine points out, "The problem with energy efficiency … is that it establishes and reproduces ways of life that are not sustainable in the long run." He points out that energy efficiency policy ignores low-energy alternatives because efficiency is relative—"this electric dryer is more efficient than that one," rather than "this electric dryer is more efficient than hanging your clothes on a clothesline."

We need to distinguish between efficiency, sufficiency, and self-sufficiency. So far, most ICT engineers have focused on the first, designing more efficient systems whose absolute energy footprint nevertheless is on the rise. A sufficient system, by contrast, does not take the environment for granted but keeps its consumption within certain limits. And "If a system can reduce its consumption of some inputs to zero, it is said to be 'self-sufficient' with regard the that input" [20]. Hilty, a leading voice in computing sustainability, argues that computing needs to be not efficient but self-sufficient: using renewable energy, slowing the obsolescence cycle, and following the principles of appropriate technology. As he suggests, "Contrary to the current 'anytime culture', people living in a self-sufficient region would have to adapt their lifestyles to the pace of the renewable energy supply" [20]. Hilty's ideal scenario omits the competition among software providers that is one of the drivers of obsolescence: "If the few basic functionalities that are needed in all types of application software would be more strictly and more universally defined, the innovation cycles for an infrastructure-type data center would slow down, and with them the hardware flow through the data center" (ibid., 2). See also the scenarios for an ICT-enabled circular economy in [52].

4 RELATED MODELLING WORK

The authors in [42] presented a bottom-up calculation that was used to estimate 2008 U.S. data center electricity demand. Moreover, the model is not limited to the U.S. only, it can potentially be used to estimate data center electricity demand within a region. The authors estimated the 2008 U.S. data center electricity demand to be 69 billion-kWh. Moreover, the study suggests that the demand can be reduced by up to 80% (to 13 billion kWh), achievable via energy efficient measures.

Shehabi et al. [60] present a similar work to the one described in [42]. The mathematical modeling was updated. The study reveals a steady annual electricity use of 70 billion kilowatt hours from 2010 to 2014 in the U.S. Furthermore, electricity demand projections until the year of 2020 were performed. The model estimates three scenarios in order to show the wide range in potential electricity that could be consumed and how adopting key efficiency measures could have a positive impact (less data center electricity consumption). The three described scenarios are: Current Trends, Frozen Efficiency, and Best Practices.

The study in [5] provides an average electricity intensity of transmitting data though the internet estimate of 0.06 kilowatt-hours per gigabyte for 2015. The authors identified that the past studies intending to calculate the average electricity intensity of the internet, diverged greatly not because of the methodology they used, but due to differences in the system boundaries, assumptions used, and the year in which the data was gathered to compute the estimates. The study revised 14 studies that provide estimates of electricity intensity, converted them to kilowatt-hour per gigabyte, recalculate the estimates if necessary (so that every estimate has the same system boundary). According to the authors, all of the 14 studies used one or more of the following methods: modeling, annual electricity consumption (AEC), direct measurements, and extrapolation.

Ejembi et al. [17] claim that by adjusting the Netflix's video quality settings, savings up to 100 GWh per year can be achieved. This has also been amplified by The Shift Project (2019) [44] and [54, 54]. Although the energy estimation was a very crude calculation (using Fermi estimates), the authors investigated the energy usage for video encoding and decoding for different popular codecs on a desktop hardware system. The study concludes that there is a mean difference of $\sim$ 3.7 Watts between Netflix lowest and highest quality.

Some studies as the one presented in [62] look at the computing devices energy consumption with regard to global consumption. The study focuses on portable computing devices. The authors estimated an overall energy consumption due to data centers in 2010 to be 350 million MWh globally; this figure takes into account heating, ventilation, and air conditioning (HVAC) and lighting. If HVAC and others are deducted from the 350 million MWh figure, the estimation leads to 175 MWh direct energy consumption.

The authors in [3] presented a review in order to evaluate the consistency of different life cycle assessment (LCA) studies for desktop computers, laptops, mobile phones, and televisions. The study reveals the inconsistencies between different studies are due to subjective choices, different system boundaries between the studies, and life time rather than the lack of standardization. The literature review in this paper was dated having many of the references belong to websites that no longer exist. A more extensive review of data center energy consumption modeling is presented in [13].

Schien [57] estimated the energy intensity of the core networks in 0.052 kWh/GB. They *exclude access networks*, whereas [4] includes them. They chose their parameters for the model to be: Edge Switch Energy Intensity; Router Energy Intensity; Route length and Router Count; WDM Terminals and Amplifiers in Edge and Core; Network utilization; PUE and redundancy; and, Undersea cable. The contributions in edge, metro, and long haul networks are 0.0043 kWh/GB, 0.02 kWh/GB, and 0.028 kWh/GB, respectively.

Andrae et al. [4] consider the fixed area networks (FAN) to be the core network, wired access network, costumer premises equipment, and wireless local area networks. Note that [57]'s estimation was around 0.02–0.18 kWh/GB for digital services in 2014 for metro and core network scopes, which *excluded* consumer devices.

5 MODELLING METHODOLOGY

We combine several models from peer-reviewed publications to create a holistic end-to-end calculator to calculate the impact of streaming video. The model has four main sub-models: data center, internet, user device, and time-of-day. Fig. 2 depicted the different systems that a stream passes through when being viewed on a device. End-to-end means from the start where the video is stored, to streaming the video over to Internet, to the viewing device (the final destination). Additionally, we include the environmental impact of the having the device manufactured. A novel part of our calculation is the time-of-day model which accounts for the impact based on simultaneous connections for a given time period. We also calculate the impact of unused energy.

5.1 Data Center Model

Shehabi et al. [60] presented a bottom-up model to estimate the electricity usage of data center electricity demand in the United States of America over a 20 year period. Although their work focuses on the United Sates of America, they provide a clear mathematical model and baseline figures for the average data center types. The data center energy model can be computed as:

$$E = E^{S} + E^{ST} + E^{P} + E^{I} \tag{1}$$

where E^{S}, E^{ST}, E^{P} and, E^{I} are the electricity usages of the servers, storage, network, and infrastructure equipment, respectively; this model requires us to know intimate details of each and every data center, making in not easily generalizable.

Table 1: Data Center Classifications [60]

Classification	No. of Servers	Demand (kW)
small data center	100–500	50
medium data center	500–5,000	240
big data center	≥5,000	≥2,500

In contrast, Schomaker et al. [58] divide data centers into three classifications: small, medium, and big (see Table 1). These classifications in Schomaker allow us to create a more generalized model without knowing specific data center information as in Shehabi's model.

Based on Schomaker's classifications in Table 1 we have modelled *data center energy per stream* in kWh by:

$$DC_{energy} = \frac{Demand \times Time}{Streams} \tag{2}$$

where *Demand* is the power demand in kilowatts (kW) based on the data center size, *Time* is the length of the video being streamed in hours, and *Streams* is the number of simultaneous streams being served by the data center. The more streams a data center serves, the smaller each stream's carbon footprint will have.

We note that Hintemann [21] discussed the idea of hyper-scale data centers as being more energy-efficient. However, with the introduction of cloud computing and edge computing, it becomes more challenging to identify the location of servers and measure their electricity consumption. For this reason, we do not include hyper-scale data centers as part of our model.

5.2 The Internet Model

The structure of the internet that we will be adopting is the one considered in [57]. A common way of decomposing networking equipment is to divide it into four layers: access, edge, metro, and long haul. The energy intensity of a device is the ratio between its energy consumption and its actual data throughput. Nominal data capacity differs from the actual data throughput, as the former takes into consideration unused capacity.

The chosen model encompasses metro, backhaul, and undersea cables. The energy intensity for the metro segment is estimated per router and then summed up over all the routers involved. The model also considers optical transport networks, which are modelled by the energy intensity per device and then summed up over all the transport devices. Finally, long-haul networks are modelled in a very similar manner to the metro network, with the slight difference being the lower energy intensity per router and the higher number of optic transport devices that the backhaul network possess.

The authors in [57] modelled the energy intensity of the edge and core networks by describing each of the contributing parts (i.e., edge switch, router, router length, router count, wavelength division multiplexing (WDM), amplifiers in edge and core networks, network utilization, PUE, redundancy, and undersea traffic) of the network with random variables. Later, a sensitivity analysis is performed in order to identify the model parts that have a bigger impact on the model result [57]. Monte Carlo simulations can help understand the impact of communication channel bandwidth and dynamic load balancing [18].

Table 2: Core Network Energy Intensity [57]

Network Part	Intensity (kWh/GB)
edge	0.0043
metro	0.0200
long haul	0.0280
Total	**0.0523**

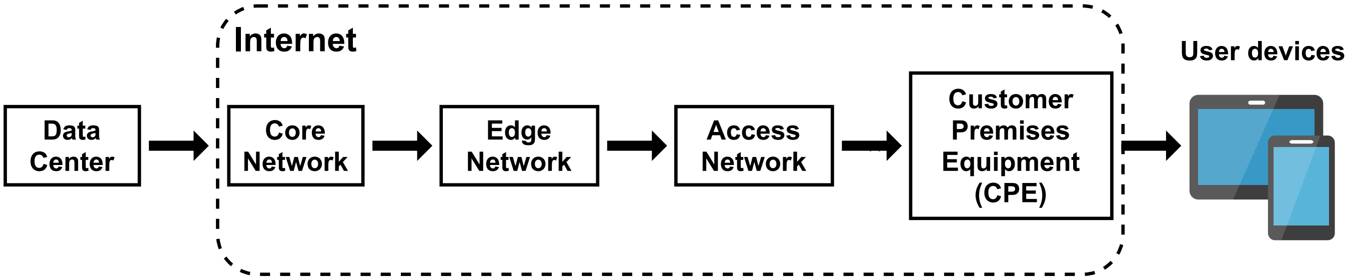

Figure 2: Block diagram of network components for streaming media. Data Center, Internet, and User Devices are some of the models for our calculator. Other intrinsic models such as manufacturing footprint cost and time-of-day as not part of this diagram but are included in our calculations.

The final average estimates for the energy intensity of data traffic through the edge, metro and long haul networks, which include undersea cable links, are noted in Table 2. Using Table 2 we can calculate the *core network energy* of a given steam by:

$$CoreNet_{energy} = Time \times BitRate \times Intensity \tag{3}$$

where *Time* is the length of the video being streamed in seconds, *BitRate* is the number of bits per second that can be transmitted in GB/s, and *Intensity* is the resulting Table 2 in kWh/GB.

The energy intensity of the access network and CPE can be calculated as 52 W (taken from [10]). Although their formula has some degree of uncertainty, as mentioned by the authors [10], it provides a reasonable understanding of how power is being consumed by the access networks and the CPE equipment. We can now calculate the *ISP energy* as:

$$ISP_{energy} = \frac{52 \times Time}{1000} \tag{4}$$

where 52 is the number of Watts taken from [10], *Time* is the length of the video being streamed in hours, and division by 1,000 to get the result in kWh.

It is worth noting that home access networks do not include end-user devices, but include customer premises equipment (CPE), access networks, redundancy equipment, cooling and other overhead, as well as fibre optics [10]. This is a matter of semantics. The concept of the internet does not include end devices but only the infrastructure connecting them. What the model consists of: CPE and Access Networks, Overhead: PUE and Redundancy, and Fibers.

To calculate the total energy used by the stream over the Internet, we can simply add Eq. (3) and (4) as such:

$$Net_{energy} = CoreNet_{energy} + ISP_{energy} \quad . \tag{5}$$

5.3 User Device Model

"It seems more meaningful always to assess network energy and the energy of the devices separately, and to add them up when needed – for example, for the assessment of the energy needs of the specific service" [10]. Following, we have found power demand and energy usage statistics for many user devices that can be used to watch streaming videos (see Table 3). We can calculate the amount of energy used to stream on a *user device* by:

$$Device_{energy} = Demand \times Time \tag{6}$$

where *Demand* is the power demand in kilowatts (kW) of a given user device listed in Table 3, and *Time* is the length of the video being streamed in hours.

Table 3: User Devices [24, 25, 55]

Device	Demand (Watts)	Energy* (kWh/year)	Lifespan (years)
desktop PC	250.0	91.25	5–7
game console	190.0	69.35	~6
laptop	7.4	2.70	5–7
plasma TV	210.0	76.65	7–10
smart phone	3.7	1.35	2–4
smart TV	43.0	15.70	7–10
tablet	3.7	1.35	~7

(*) Assuming the device runs 1 hour everyday for 1 year.

When calculating the energy used by a user device, it is essential to consider the manufacturing cost. The "production energy makes up 85–95% of its lifecycle annual foot-print, driven by the short average useful life of smart phones of 2 years, which is driven by the telecom membership business model. Clearly this business model, while highly profitable to the smartphone manufacturers and the telecom industry, is unsustainable and quite detrimental to the global efforts in GHGE reductions." [6]. It is difficult to calculate the total cost because the exact lifetime of a device in not easily known (see Table 3 for lifetime ranges). As a result we calculate this cost for the time the device is used based:

$$Manuf_{cost} = Device_{energy} \times 90\% \tag{7}$$

where $Device_{energy}$ is determined from Eq. (6) in kWh, and 90% is the median of the 85–95% range given in [6].

5.4 End-To-End Streaming Model

Given that we have defined all of our sub-models where we can calculate the energy used by the Internet and User Device (i.e., baseline), they do not depend on the number of simultaneous streams as done with Data Centers. The Baseline energy calculation is defined as:

$$Baseline_{energy} = Net_{energy} + Device_{energy} \quad . \tag{8}$$

The final calculation to determine the amount of energy (kWh) used by the stream is defined as:

$$Steam\ Impact = DC_{energy} + Baseline_{energy} + Manuf_{cost} \quad . \tag{9}$$

5.5 Time-Of-Day Model

The hourly data demand (and data center load) across a day fluctuates. More energy is utilized when demand/load is high in a data center. However, if demand is low, there is unused energy — systems/equipment cannot ramp down, then up when there are momentary demand/load fluctuations, as the fluctuations can change faster than the ability to ramp up/down. We created an hourly time-of-day model based on [47] to examine the impact of fluctuating demand. We assume for simplicity that this is a representative survey and use the *total* and *watching* category data demand from [46].

If we include video embedded in *social media and online media* and *listening* the demand fluctuations would be significantly higher. However, these figures are extremely difficult to estimate.

Firstly, using the dataset [46] from [47] (denoted as *traffic*) we calculate for each hour h the percentage of traffic that is video streaming:

$$Net_{watching}[h] = \frac{traffic[\text{`watching'}][h]}{traffic[\text{`total'}][h]} \times 100 \tag{10}$$

where h is the hour from $0, 1, ..., 23$, $traffic[\text{`watching'}]$ is the kB of data just for streaming videos for each hour $h$, and $traffic[\text{`total'}]$ is the kB of data just for all types of traffic for each hour h. Once calculated, we can then use this model to calculate the potential load on streaming data centers for each hour h of the day:

$$DC_{load}[h] = \frac{Net_{watching}[h]}{max(Net_{watching})} \times 100 \tag{11}$$

where we use the $max()$ function to normalize the data center load DC_{load} for each hour h. For simplicity, we assume that this maximum would have the data center at 100% utilization with no unused energy. We can now calculate the unused energy (kWh) for each hour h of a data center by:

$$Unused_{energy}[h] = Streams \times DC_{load}[h] \times DC_{energy} \tag{12}$$

where $Streams$ is the number of simultaneous streams being served by the data center, which is the same value in Eq. (2).

6 EXAMPLE CALCULATIONS

Here we perform some calculations that show the carbon footprint of a one-hour stream, as well as, calculations to show the impact of unused energy in data centers.

6.1 The Carbon Footprint of a Stream

We calculate the network energy consumption from watching one hour of video streamed from Netflix. We assume that the user is based in the UK and watching a video stream on his plasma TV connected via WiFi to a DSL Modem with an integrated WiFi router connected to a DSLAM and then the rest of the internet. These assumptions are very similar to the ones provided in [57]. We use a bit-rate of 1500 KB/s according to [45]. The data center energy consumption is calculated based on a number of simultaneous streams from one high-end server in a big data center as per [49] and assuming a linear model for the server consumption. See Table 4 for detailed numbers and results.

Table 4: Calculation numbers used and results

Video Input/Output Data	Amount	Unit
Input parameters:		
Netflix bit rate @ 12 Mbps [45, 49]	1500	KB/s
Data volume	5.4	GB
Time	3600	s
Energy intensity	0.052	kWh/GB
PUE	2	—
Power demand for CPE	8	W
Idle overhead	6	—
Power demand for big data centers	2.5	MW
User device (plasma TV, see Table 3)	210	W
Output energy consumption:		
Big data center from [60]	2.500	MWh
Internet (core & ISP)	0.334	kWh
User device + Manufacturing Cost	0.399	kWh
Energy/Stream (1 stream)	**2.501**	**MWh**
Energy/Stream (10k simul. streams)	**0.983**	**kWh**
Energy/Stream (50k simul. streams)	**0.783**	**kWh**

Our model finds that streaming one hour of Netflix videos is roughly between 0.783–0.983 kWh of energy consumption depending on the number of simultaneous streams (10,000–50,000) being streamed from the data center. Figure 3[top] extrapolates that further to find that when a big data center can serve about 50,000 simultaneous streams, the energy attributed to each stream shrinks to a negligible amount.

To understand what energy means in different terms, we used the US EPA Greenhouse Gas Equivalencies Calculator [65] to find equivalent comparisons, which we summarize in Table 5 for 10,000 and 50,000 simultaneous streams from a data center. Two interesting comparisons are that one hour of Netflix streaming is equivalent to about 1 kg of CO_2 or the burning of 0.17–0.21 kg of coal.

Figure 3[middle] shows the energy/stream calculation for a one-hour stream. The Data Center was set to 10,000 simultaneous streams as demand fluctuated over the day using our time-of-day model. The resulting energy/stream ranges between 0.9–1.3 kWh per stream.

6.2 Unused Energy in Data Centers

Our final calculations examined the effect of streaming demand on energy used by the data center. Figure 3[bottom] shows that small changes in streaming demand (i.e., number of simultaneous streams) have significant effects on how much energy goes unused in a data center. On average, this unused energy was 755 kWh with a peak of 1,292 kWh for the 9am period.

Table 6 is a similar equivalent comparison using the US EPA Greenhouse Gas Equivalencies Calculator [65] for unused energy in data centers. Two interesting comparisons are that one hour of Netflix streaming is equivalent to about 327 (average) and 559 kg

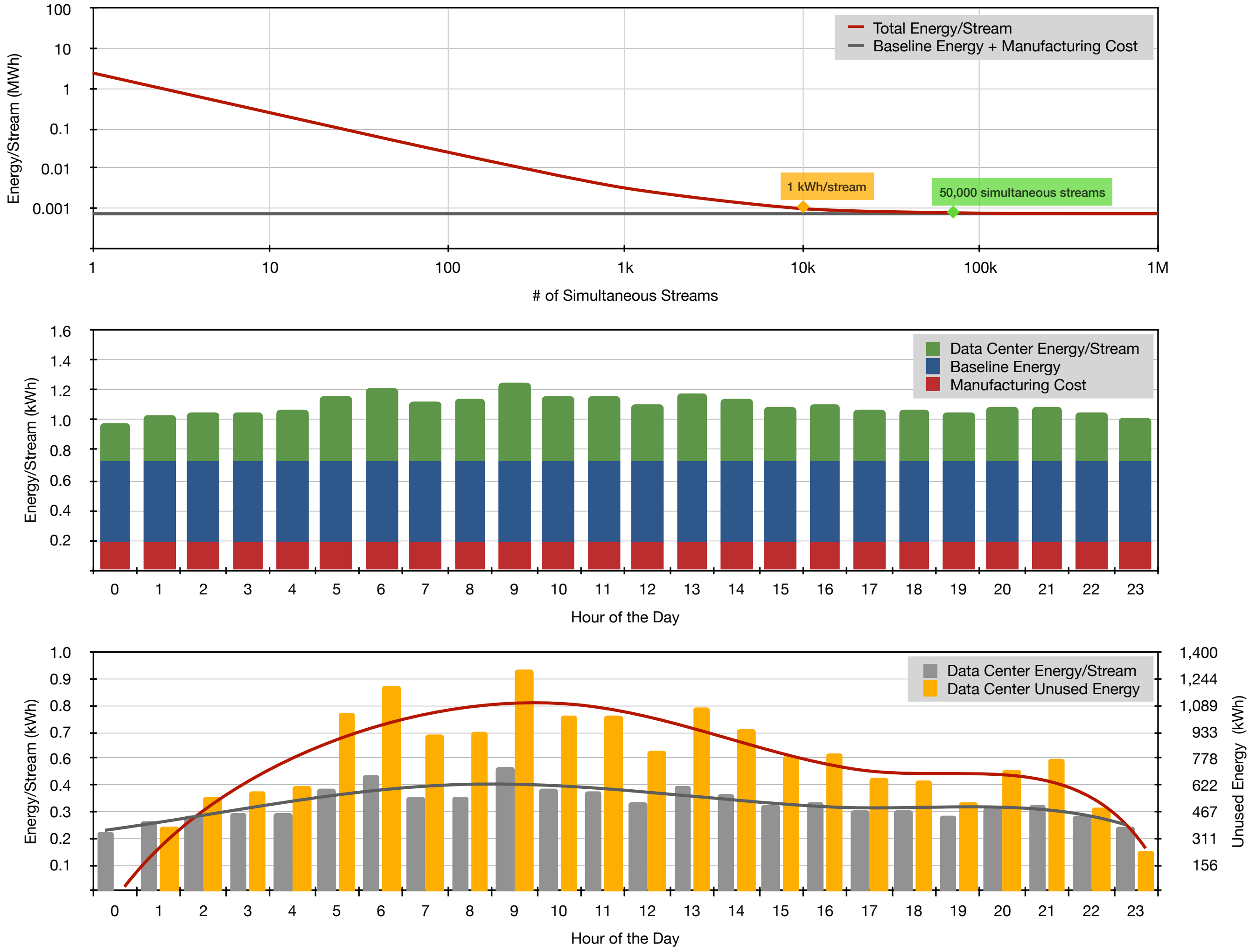

Figure 3: All charts look at per-hour or an hour of streaming. *Manufacturing Cost* is the amount of energy used to produce the device (e.g., plasma TV is used). *Baseline energy* is the amount of energy not including data center energy. *Energy/Stream* is calculated using data center energy only. [TOP] As the number of simultaneous streams increases for one hour from a big data center, the energy attributed to each stream shrinks to a negligible size at about 50,000 simultaneous streams. [MIDDLE] The energy cost per stream (from end-to-end) fluctuates over a 24-hours based on the number of simultaneous streams. [BOTTOM] While the trend is relatively even for energy/stream (grey), the trend (red) for *unused Energy* is much more prevent. Minor changes in the number of simultaneous streams have significant effects on how much energy goes unused in a data center.

(max) of CO_2, or 145.9 (average) and 249.6 (max) litres of diesel consumed.

Our finding corroborates those of others who conclude that streaming more data results in greater efficiency. For example [38] write "High quality video streaming can be 100× more energy efficient (0.01 kWh/GB)...", and [54] reach similar conclusions. However, as we have explained, energy efficiency is not at all the same as a reduction in energy consumption. An infrastructure engineered to anticipate future demand becomes efficient when it is operating at capacity.

7 BROADER DISCUSSION

The ICT consumption of wealthy countries is by no means saturated, despite the expectations of some ICT engineers [38] that desire for higher-resolution streaming is leveling off. Cisco's science-fiction scenarios of 4K, 8K, and holographic streaming would demand yet more infrastructure and make more devices obsolescent, prompting new consumption and driving streaming's carbon footprint yet higher. It is also important to note that, as Hazas et al. [19] point out, a significant and rising proportion of data demand responds not to consumers' attention but to machine-to-machine communications, such as software updates, data backups, and data-intensive Internet

Table 5: Comparing Equivalencies for kWh/stream

Simultaneous streams:	**10,000**	**50,000**
kWh/stream energy used (from Table 4)	0.983	0.783
kg of Carbon Dioxide (CO_2) equivalent	0.425	0.339
Greenhouse gas emissions from:		
passenger vehicles driven for 1 year	< 0.001	< 0.001
km driven by an avg. passenger vehicle	1.770	1.353
CO_2 emissions from:		
litres of gasoline consumed	0.218	0.173
litres of diesel consumed	0.191	0.150
kg of coal burned	0.213	0.170
tanker trucks' worth of gasoline	< 0.001	< 0.001
homes' energy use for one year	< 0.001	< 0.001
homes' electricity use for one year	< 0.001	< 0.001
railcars' worth of coal burned	< 0.001	< 0.001
barrels of oil consumed	0.001	< 0.001
propane cylinders used for home bbq	0.017	0.014
coal-fired power plants in one year	0.000	0.000
natural gas-fired power plants in one year	0.000	0.000
number of smartphones charged	51.700	41.200
Greenhouse gas emissions avoided by:		
kg of waste recycled, not landfilled	0.091	0.091
garbage trucks of waste recycled	< 0.001	< 0.001
trash bags of waste recycled	0.018	0.015
wind turbines running for 1 year	0.000	0.000
incandescent lamps switched to LEDs	0.016	0.013
Carbon sequestered by:		
tree seedlings grown for 10 years	0.007	0.006
m^2 of forests in 1 year	2.023	1.619
m^2 of forests preserved in 1 year	0.000	0.000

Table 6: Comparing Equivalencies of Unused Energy

Unused Energy in Data Centers:	**Avg**	**Max**
kWh unused used (from Fig. 3[bottom])	755	1,292
kg of Carbon Dioxide (CO_2) equivalent	327	559
Greenhouse gas emissions from:		
passenger vehicles driven for 1 year	0.07	0.12
km driven by an avg. passenger vehicle	1,305	2,232
CO_2 emissions from:		
litres of gasoline consumed	167.3	286.0
litres of diesel consumed	145.9	249.6
kg of coal burned	163.8	280.3
tanker trucks' worth of gasoline	0.004	0.007
homes' energy use for one year	0.041	0.070
homes' electricity use for one year	0.064	0.109
railcars' worth of coal burned	0.002	0.003
barrels of oil consumed	0.756	1.300
propane cylinders used for home bbq	13.3	22.8
coal-fired power plants in one year	0	0
natural gas-fired power plants in one year	0	0
number of smartphones charged	39,730	67,988
Greenhouse gas emissions avoided by:		
kg of waste recycled, not landfilled	102.5	175.1
garbage trucks of waste recycled	0.016	0.028
trash bags of waste recycled	14.1	24.2
wind turbines running for 1 year	0.0001	0.0002
incandescent lamps switched to LEDs	12.4	21.2
Carbon sequestered by:		
tree seedlings grown for 10 years	5.4	9.2
m^2 of forests in 1 year	1566.1	2675.0
m^2 of forests preserved in 1 year	8.1	16.2

of Things applications, whose number of devices was projected, in 2016, to reach 21 billion by 2020.

Meanwhile, as media corporations, platforms, and telecoms expand into less-infrastructured countries, and users gain access to high-speed internet and the new devices it requires, the global streaming carbon footprint is rising.

Energy efficiency appears to be unquestioned as a goal in the ICT literature, even among those ICT engineers who claim to be interested in sustainability, with very few acknowledging that efficiency is a goad to expansion, not a limit. Efficiency is the ICT sector's defensive response to demands by telecoms and video streaming services (and AI and cryptocurrency) to underwrite the cost of their energy-hungry products. Limiting the flow of data is not an option; instead, they ask governments to absorb the cost. For example [41] recommend that "greater public funding should be allocated to advancements in computing, data storage, communications, and heat removal technologies that may extend the IT industry's historical efficiency gains well into the future" (986). This call parallels that of Alphabet CEO Eric Schmidt urging US government to invest in artificial intelligence and communication infrastructure. "If we are to build a future economy and education system based on tele-everything, we need a fully connected population and ultrafast infrastructure. The government must make a massive investment–perhaps as part of a stimulus package–to convert the nation's digital infrastructure to cloud-based platforms and link them with a 5G network" [28].

These are not recommendations that we advocate, because they are environmentally unsustainable and advocate government investment in shareholder corporations.

Instead, with De Decker, we advocate a speed limit to the Internet, for example through data quotas [15, 19] or a carbon tax on streaming platforms. Sharing the view of Morley, Widdicks, and Hazas [47], we critique the carbon-intensive ideal of net neutrality—that all citizens should have equal access to high-speed internet. We agree with Lobato [36] that net neutrality is "grounded in a first-world idea of the internet, premised on an assumption of unbounded capacity. It does not ring true with how the internet is experienced in many countries." Interestingly, The Shift Project [44] argues that regulation is compatible with net neutrality if we consider the criterion that the Internet be for the common good. We embrace this redefinition. Leidig and Teeuw [35] advocate a basic level of ICT development for every nation for emergency preparedness, but not for high-resolution streaming on demand. Similarly, the Data Poverty Index devised by Leidig and Teeuw measures the capacities necessary for sustainable development and disaster risk reduction based on internet speed; number of computers per household; mobile phone subscriptions; mobile network coverage; internet users as percentage of population; and participation in higher education. A basic degree of connectedness and access is necessary for all, but it is important to distinguish between these needs and the profit-driven demand for high-definition streaming.

Much of the wastefulness of streaming, as well as other ICT applications, results from competition between shareholder corporations. Hilty's [20] ideal scenario omits the competition among software providers that is one of the drivers of obsolescence: "If the few basic functionalities that are needed in all types of application software would be more strictly and more universally defined, the innovation cycles for an infrastructure-type data center would slow down, and with them the hardware flow through the data center" (ibid., 2). See also the scenarios for an ICT-enabled circular economy in [52]. Competing platforms often result in layers of infrastructure [19]: a more efficient solution would be for federal governments to own ICT infrastructure and companies lease throughput.

The Slow Tech movement steps back from the "techno-positivist assumption that more and richer digital services are necessarily better for individuals and society"[53](1332). The more pessimistic collapse informatics (e.g. Tomlinson et al. 2013 [64], Lambert et al. 2015 [32]) explores post-peak oil scenarios in which low-power networking is no longer optional, but instead becomes a necessity due to energy-intermittent future; this would also apply to other energy-constrained situations, such as disaster recovery or off-grid installations in developing countries. The authors introduce the concept of "graceful decline." Hilty [20], a leading voice in computing sustainability, argues that computing needs to be not efficient but self-sufficient: using renewable energy, slowing the obsolescence cycle, and following the principles of appropriate technology. As he suggests, "Contrary to the current 'anytime culture', people living in a self-sufficient region would have to adapt their lifestyles to the pace of the renewable energy supply" [20]. Like these authors, we advocate that overdeveloped countries take more lightly infrastructured countries as a model and learn to enjoy slow, interrupted, low-resolution media.

8 CONCLUSIONS

So, what is the carbon footprint of streaming media? We have presented a reasonable model that considers the more cited models published within the literature. As we have demonstrated, the most likely actual footprint value sits somewhere near 0.8 kWh per stream at any given time. Using the US EPA Greenhouse Gas Equivalencies Calculator, we find that one hour of Netflix viewing consumes between 0.8–1.0 kWh of energy consumption depending on the number of simultaneous streams from the data center which is equivalent to the average passenger vehicle driving 1.4–1.8 km, or about 0.2 kg of coal being burnt. We also showed that there is a large portion of unused energy (on average 755 kWh) for big data centers which is 327 kg of CO_2 or burning 164 kg of coal.

8.1 Future Work

Future work would include adding more specific locations (city/country, postal code, or geolocation) of the data center and end user as part of the calculator. Additionally, more real-world data is needed to verify the ranges presented here and pin-point a more accurate number. However, it is likely that for this to happen it would require considerable public pressure and government regulations to bring this data to light.

8.2 An Open Call

We call on industry (telecom, hosting, and streaming providers) to publish more factual numbers — not to remain secretive and silent. Allow researchers to verify and understand the impact of streaming on the environment.

8.3 Calculator Code

Our calculator was coded using a spreadsheet (Numbers) and has been released as open source. It is available at https://github.com/compsust/StreamingCalc.

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