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Towards Estimating the Carbon Footprint of Video Streaming

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Abstract—Video streaming dominates the Internet traffic. Assessing the carbon footprint of video streaming has received recently a significant attention with a number of models proposed to associate a CO₂ cost to one hour of streaming.

In this work, we compare the modeling assumptions and computation methods used by five recent works to inform the debate. Indeed, initial results can be at odds, with up to one order of magnitude difference in the estimates. Our contributions are: (i) we relate the difference in the results primarily to the perimeter of the study, e.g. including production cost or not, (ii) we question some of the modeling assumptions made using a real deployment of a streaming server in a controlled environment with up to 2000 clients and (iii) we propose a technique to reconcile the models and obtain a CO₂ estimate in between 60 and 140 grams when considering the average worldwide carbon intensity of electricity.

Index Terms—Video Streaming, Carbon footprint.

I. INTRODUCTION

Video streaming dominates the Internet traffic [5], [20] and constitutes a major driver of the Internet infrastructure deployment and updating process [10]. This calls for a clear assessment of its environmental impact. The topic is controversial as exemplified by the SHIFT Project vs IEA dispute [11]: the SHIFT project publicly advertised an estimate of 261.4 grams of CO₂ for one hour of video streaming while IEA experts obtained 26.5 grams of CO₂, an order of magnitude smaller value. More generally, a number of models have been developed recently to assess the CO₂ emissions of one hour of video streaming. We compare, in the present work, five such models: LIMITS[14], CARBONTRUST [24], RENATER [8], IEA [11] and SHIFT [18].

Our objective is to investigate the differences observed in the estimates provided by these models. This requires a precise investigation of the perimeter of the study, the modeling assumptions as well as the input values of each model. Our contributions can be summarized as follows:

- We relate the difference in the results to the perimeter of the study, e.g. including gray energy (production cost) or not, and also to the choice of inner parameters of the

models, e.g. the energy efficiency per GB of the network, or the exact power consumption of the TV or smartphone of the end user;

- We analyze and compare the models under study in a number of key scenarios, e.g. a streaming service delivering high quality content to a large screen device or a service streaming videos to a smartphone;
- We question some of the modeling assumptions made using a real deployment of a streaming server in a controlled environment with up to 2000 clients;
- We propose a technique to reconcile the models and obtain a CO₂ estimate in between 60 and 140 grams when considering the average worldwide carbon intensity of electricity and a fixed access network.

II. MODELS ANALYSIS

Borrowing the life cycle assessment (LCA) vocabulary, the functional unit we consider corresponds to streaming one hour of video from a server in the cloud to an end user equipment. Our focus is on global warming (CO₂ emissions), which is one of the eight impact factors typically considered in LCA. Other factors like water consumption are also important, see for instance [23] for the case of data centers in the US or [12] for the case of AI. They are however not taken into account in the models we focus on.

A. High level overview

Let us first provide a high level overview of the common modeling assumptions shared by all these models. The classical approach to tackle the problem is to break the streaming distribution scheme into three tiers: (1) Data center, (2) Network, (3) User Equipment.

The data center is sometimes modeled as a whole, or as a single streaming server. The network might be the fixed network, the mobile network or a combination of both to account for typical usage. As for the user equipment, they primarily differ based on the size of their screen, e.g. smartphone or wide-screen TV, which affects the encoding quality of the content chosen by the content provider (users in general keep the default encoding quality chosen by the platform [25]).

As network and data centers are shared facilities, all models use as unit the amount of traffic serviced by network devices and servers. This means that one needs estimates for both the total energy consumption and the total traffic conveyed or processed by the device to obtain a per byte estimate. It

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is clearly a complex task as data centers operators and ISPs may not wish to publish this level of detail [24] or simply experience difficulties to deploy the necessary measurement infrastructure to do so.

As compared to the data center and network, the end user equipment is a non shared facility, and one traditionally evaluates its impact with respect to usage duration, hence one hour in our case.

Usage and manufacturing costs need to be aligned, when both costs are estimated (which depends on the exact model). Indeed, the usage cost depends on the number of years of utilization while the production cost is a fixed cost, typically obtained from the manufacturers environmental sheets [13] which provide total CO₂ emissions for the different phases of the production (from abiotic resources extraction, pre-manufacturing, e.g. integrated circuits production, to manufacturing and product delivery). As for usage, it can be reported either in kWh or CO₂ depending on the study. Translating kWh into CO₂ is country dependent, since each country features a specific mix of technologies (solar, wind, coal, etc.) to produce electricity [1]. To work around this conversion issue, we extract the usage costs of each model in kWh, and later apply the same electricity factor¹ to all models outputs. Unless stated otherwise, we use the french electricity factor of 108 g of CO₂/kWh similarly to [8].

The five models we consider are: LIMITS [14], CARBONTRUST [24], RENATER [8], IEA [11] and SHIFT [18]. We named them based on the name of the organization (Shift, Carbontrust and IEA), the conference where it was published (LIMITS) or the network where the measurements were made (RENATER).

The RENATER model is not a video streaming model per se but a video conferencing model. The model is complex as it accounts for service details such as the number of virtual machines deployed or the maintenance cost. We consider here a simplified version with a physical (non shared) server. A key point of the RENATER model is that it is calibrated with actual measurements made in the Renater network and data center since the application (called Rendez-vous), the network, the data center and the clients are all operated by Renater.

Due to space constraints, we will detail the modeling approaches for the data center and only sketch the key differences between the models for the network and user equipment. Please refer to our companion paper [15] for the details of the network and user equipment tiers. Note that we do not have access to the detailed equations of the IEA models but to an online simulator [11]. The procedure to extract the data from the simulator is detailed in section III-B.

B. Data centers Contribution

1) **LIMITS:** The energy consumption is computed at the scale of the data center [14]. The authors consider three typical sizes of data centers in terms of number of servers and power

¹The energy factor indicates how much CO₂ grams are emitted to produce one kWh of electricity.

consumption and divide this consumption by the number of active streams. The corresponding values vary between 50 kW and 2500 kW for the power consumption (based on [22]) and between 10k to 50k streams for the workload. The power consumption per stream can thus vary from $\frac{2500kW}{10k} = 250W$ to $\frac{50kW}{50k} = 1W$ for a given stream. The resulting data center energy per stream is computed as follows:

$$DC_{energy} = \frac{Pw \cdot D}{N_{streams}} \quad (1)$$

where Pw is the power demand in kilowatts (kW) based on the data center size; D is the duration of the video being streamed in hours (1 hour in our case) and $N_{streams}$ is the number of simultaneous streams being served by the data center.

2) **CARBONTRUST:** The energy consumption at the data center is estimated as follows:

$$DC_{energy} = ID_C \cdot D \quad (2)$$

where ID_C is the energy intensity of the data center, estimated as 1.3W. When compared to the LIMITS case, such a value corresponds to a small DC consuming 50 kW operating at the maximum load of 50k streams in parallel (1W/stream).

3) **RENATER:** This model considers both usage and manufacturing costs. The usage cost is computed as follows:

$$DC_{energy} = C_{dc}^{year} \cdot \frac{Q}{\text{Traf}_{dc}^{year}} \cdot PUE \cdot EF \quad (3)$$

where C_{dc}^{year} is the annual energy consumption in kWh of the data center; Q indicates the traffic generated by the user and Traf_{dc}^{year} is the traffic serviced by the datacenter in one year. PUE stands for Power Usage Effectiveness. It is the ratio of the electricity used to power the IT (servers and network devices) to the total energy consumed by the data center that includes notably air conditioning. RENATER considers a PUE value of 1.5, i.e. a 50% overhead for non IT operations in the data center. EF is the electricity factor, i.e. the number of grams of CO₂ emitted to produce one kWh. We will set aside this factor when comparing the usage contribution of the different models as they use different EF values from different countries, e.g. France for RENATER and USA for LIMITS. As compared to the other models, the RENATER model further considers the manufacturing cost of the data center computed as follows:

$$DC_{man} = \text{Prod}_{dc} \cdot \frac{D}{\text{Life}_{equip}} \quad (4)$$

where Prod_{dc} is the total manufacturing cost (provided by the manufacturer) in kg of CO₂ and Life_{equip} is the life time of the equipment.

4) **SHIFT:** The Shift project estimates the data center energy consumption as follows:

$$DC_{energy} = EI_{dc} \cdot Q \quad (5)$$

where EI_{dc} is the energy used in order to process 1 byte. It is estimated to be 7.2×10^{-11} kWh/byte [19]. Q is the video size in bytes.

C. Network Contribution

All models use a base formula of the type $I_{net} \cdot Q$ where I_{net} is the energy intensity per byte and Q the total amount of byte transferred. The CARBONTRUST and SHIFT models further differentiate between mobile or fixed network while the RENATER model also accounts for the gray energy of the network devices.

D. User Equipment Contribution

All models share the same approach for evaluating the usage cost with a formula of the type $Pw_{ue} \cdot D$ where Pw_{ue} is the power demand of the device and D , again, one hour. The RENATER model again accounts for the gray energy, based on manufacturer information. In contrast, the LIMITS model takes advantage of the observation that the gray energy accounts for the majority of the total energy during the lifetime and sets it to 9 times the usage cost.

III. RESULTS

A. Scenarios

We build typical usage scenarios as combinations of the following parameters:

- User device: TV, Laptop or Smartphone;
- Video Resolution: SD, HD or 4k;
- Network Type: fixed or mobile.

Similarly to [24], the bit rates at each resolution are the (maximum) ones advertised by Netflix at high quality for a "Web browser": SD = 2.22 Mbps, HD = 6.67 Mbps and 4k = 15.56 Mbps [16].

For the LIMITS model, we considered a large data center servicing 10k flows (low load), so as to be aligned with the CARBONTRUST model (see section II-B2).

B. IEA Model

To extract the data from the IEA web site for the IEA model, we ran all the possible scenarios in terms of type of device, video resolution and access network type with the online simulator of IEA [11]. The values, presented in table I, are in grams of CO₂. We converted them back in kWh by considering the World (2019) case and an energy factor of 340g of CO₂ per kWh, extracted from the IEA web site². We can observe from table I that the user device contribution is time-based and not volume-based, in line with the other models. In contrast, the network and data center components are volume dependent, as all the models, except the LIMITS one that accounts for the global load of the data center.

C. Overall comparison

Let us first compute the overall energy consumption for two typical scenarios: (TV, 4k, Fixed) and (Smartphone, SD, Mobile). The former can model a high quality service like Netflix and the latter a free service like YouTube, that users access from their smartphones.

User Device			
	Smartphone	Laptop	TV
SD	0.56	10.19	55.56
HD	0.56	10.19	55.56
4k	0	10.19	55.56
Network			
	Smartphone	Laptop	TV
SD	1.66	8.37	8.37
HD	5.28	8.49	8.49
4k	0	8.69	8.69
Data Center			
	Smartphone	Laptop	TV
SD	0.64	0.64	0.64
HD	2.75	2.75	2.75
4k	0	6.42	6.42

Table I: IEA model: CO₂ emissions in grams

In figs. 1 and 2, we report the breakdown for the three tiers (data center, network and user device), as well as the aggregated (total) values. We included the manufacturing costs when available. We observe that:

- IEA always returns the smallest values, among all models, while the SHIFT model features the largest ones;
- When comparing the TV and Smartphone cases, we see clearly the impact of the size of the screen on the user device cost: it is negligible for the smartphone case, and large for the TV case. Also, a higher screen requiring a higher resolution, this results in a higher load in the network;
- The SHIFT model features the highest network cost among all models, which explains most of its total cost;
- Both the LIMITS and SHIFT models have a high data center cost. In the LIMITS case, it is exacerbated by the light load we chose.

In the following sections, we will focus on the contribution of each of the three tiers for all the models. The gray energy will be treated separately.

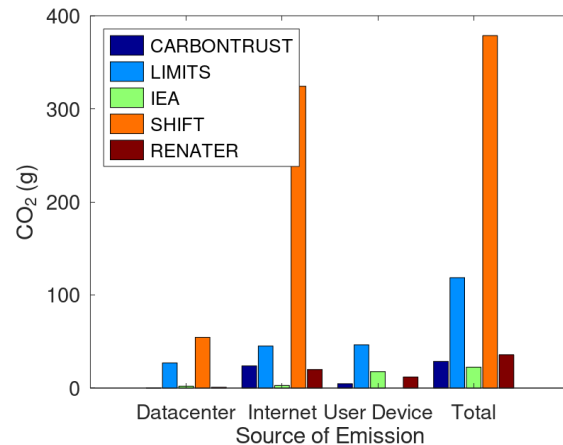


Figure 1: Total Emissions (TV, 4k, Fixed)

²<https://www.iea.org/reports/global-energy-review-2019/co2-emissions>

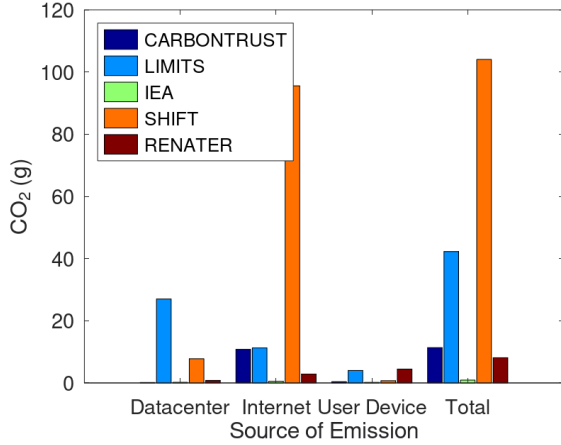


Figure 2: Total Emissions(Smartphone, SD, Mobile)

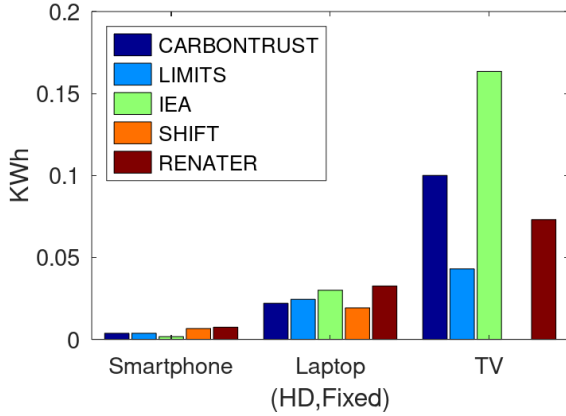


Figure 3: Comparison of the user devices (in kWh)

D. User Device

We present in fig. 3 the energy consumption (production is excluded) of the user equipment for the different models. We chose a scenario with HD resolution and Fixed Network. The results are qualitatively similar for the other cases. We express the results in kWh and not grams of CO₂, since we focus on usage.

Fig. 3 shows a clear agreement among the models for the smartphone and laptop cases. For the TV case, there is more variability (the SHIFT model does not implement the TV scenario, hence its zero value). These results can be explained as follows: the utilization contribution of the devices is computed with a similar equation of the form $Constant_{device} \cdot Time$ for all types of devices and all models. The difference between the models thus stems from the choice of the $Constant_{device}$ value. For the smartphone case, it ranges between 10^{-3} kWh for the IEA model to 7.4×10^{-3} kWh for the RENATER case. As these values are relatively similar, the final user device contributions are similar also. For the TV case, the CARBONTRUST model assumes a power demand of 100 W while the LIMITS one picked 43 W. The

IEA web page assumes a large TV of 55 inches, which might explain its large value.

E. Network

Figures 1 and 2 highlighted that the models return significantly different estimates for the network part. The IEA model reports the smallest values among all models while the SHIFT model returns significantly higher estimates. The reported values depend on the bit rate of the stream, hence the differences between SD and 4k cases. The RENATER model factors a manufacturing cost in its network footprint estimation, which accounts for about 40% of the network cost.

F. Data center

Various strategies have been considered to model the data center cost:

- The LIMITS model is a top-down model, as it considers the total energy consumption of the data center.
- The SHIFT and CARBONTRUST models are bottom-up models that focus on the streaming server consumption only. However, the SHIFT model considers that the consumption is a function of the amount of bytes while the CARBONTRUST model considers time duration. The latter means that the energy consumption is independent of the actual load.
- The RENATER model relies on the quantity of data rather than usage duration. The explicit use of the PUE further aims at accounting for the global data center contribution. In addition, the RENATER model accounts for the server production phase.
- We eventually note that the IEA model features the smallest estimate among all models.

G. Gray energy

Two of the considered models take into account the production cost: the LIMITS model that accounts for the user device production only; and the RENATER model that assigns a production cost to all tiers.

The approach of the LIMITS model is straightforward to assess the gray energy of the user device: one takes the estimated utilization cost in CO₂ and multiply it by a factor of 9. This has the clear advantage of aligning easily the production and usage costs. A drawback of the approach is however that the CO₂ emissions of the usage phase being dependent on the exact electricity mix of the country under consideration, this renders the production cost also country dependent, which is counter intuitive.

Let us now focus on the RENATER model. We report in fig. 4 both the utilisation and production cost of each tier for the (TV, 4k, Fixed) scenario used in section III-C.

We can observe that the manufacturing costs for the data center and networking are high as compared to their usage cost. This is astonishing, as one could have expected that the long lifetime of the equipment (e.g., the RENATER model assumes a 12-year lifetime for the routers and switches) would have wiped out the production cost [7]. As for the user device,

we are far from the 1:9 ratio advocated by the LIMITS model. There are two reasons behind this observation. First, the lifetime for a TV in the RENATER model is assumed to be 10 years, which is the upper bound of the values reported in [14]. Second, the RENATER model assumes that the TV is used for 3 hours per day and thus attributes a fraction of 24/3 of the production cost to the video streaming service. In contrast, the LIMITS model attributes the complete production to the streaming service, which seems unfair as the user uses others services during the remaining 21 hours of a typical day.

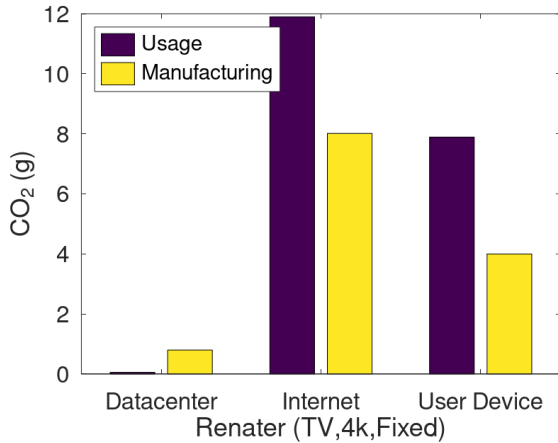


Figure 4: RENATER: Usage versus Manufacturing

IV. RECONCILING THE MODELS

In this section, we present an approach to reconcile the models, by selecting the best approach at each tier. This is a relatively easy task for the user device and network tiers, and more complex for the data center. This is why we performed a measurement campaign over the Grid’5000 testbed to inform the data center case.

A. User and Network tier

For the user device part, we picked the same power demand for all models (except IAE as the simulator does not allow to tune this value) for a specific device, e.g. 70W for the TV. For the production part of the LIMITS model, we used a 1:1 ratio and not a 1:9 ratio, as it better accounts for the service usage, as discussed above.

Concerning the networking part, the CARBONTRUST and LIMITS models feature similar results while the IEA model is way smaller and the SHIFT model way higher. As advocated by the CARBONTRUST authors, a key reference for the carbon footprint estimation of the network during its utilization phase is [4]. This paper focuses on the usage energy of the Internet and reconciles the previous observed estimates by proposing a simple empirical law that states that the energy consumption of the Internet “has decreased by half approximately every 2 years since 2000”. Following their model, one expects to reach 0.01 kWh/GB in 2020. This is in line with the measurements that fuel the RENATER model.

Indeed, table 11 (p35) of [8] reports an network emission factor for a fixed network equal to 1.7×10^{-3} kg of CO₂/GB, or 0.015 kWh/GB³, which is close to 0.01 kWh/GB. We thus used this value also for the SHIFT model.

Note that the above results are valid for the fixed part of the network and not for the mobile access network, which we leave for future work.

B. Data center tier

The Grid’5000 testbed allows to book dedicated physical servers and track their energy consumption with physical wattmeters [9]. We set up an experiment with one streaming server and up to 2000 clients. Clients arrive in batches of 200 clients (fig. 5a). and request the same video at the same quality level. There is thus a single session. The streaming server is in a dedicated physical server while clients are deployed in containers in other physical servers.

The experiment being made in a controlled environment, all runs are very similar and we present a single representative trajectory of the system. While the bit rate of the server reaches 7Gb/s with 2000 clients⁴ (fig. 5b), a key observation is that the CPU consumption remains very low as the streaming server acts as a cache servers. Indeed, its main task consists in transferring video chunks from the RAM to the network interface card, resulting in a number of software interruptions (softirq), which are not CPU intensive. The maximum observed CPU usage is thus about 3% (fig. 5c). As a consequence, the power consumption of the server raises from 75 W (with 200 clients) to at most 80 to 100 W with 2000 clients (fig. 5d), where each boxplot is obtained with all the one-second long samples in the corresponding phase (constant number of clients, see fig. 5a) of the experiment. Thus, the server consumption is in the range 0.05-0.3 W/client, quite in line with the CARBONTRUST model assumption of 1W per stream. Note that this does not rule out the LIMITS model approach, which considers that if a data center is devoted to a single service, one should consider also idle servers, hence the total consumption of data center. Clearly, more efforts should be done to understand real deployment, like the one of Netflix⁵ that mixes data centers and their openconnect CDN. In particular, all the hardware, including storage and CDN servers should be accounted.

C. Adjusting the values

In addition to the changes discussed in section IV-A, we further updated the SHIFT model. Indeed, after discussions with the main author of the initial model, we updated the values for the data center efficiencies based on [3].

We present in fig. 6 the (TV, 4k, Fixed) scenario, which corresponds to the case of a fixed access network that the RENATER and SHIFT models take into account. One observes that some discrepancies remain but the results become clearly more similar. A clear tendency is that the network and the

³when using the electricity factor of France used in the RENATER model of 108 g of CO₂ per kWh).

⁴We used a video encoded at an average bit rate of 3.5 Mb/s.

⁵<https://openconnect.netflix.com/en/appliances/>

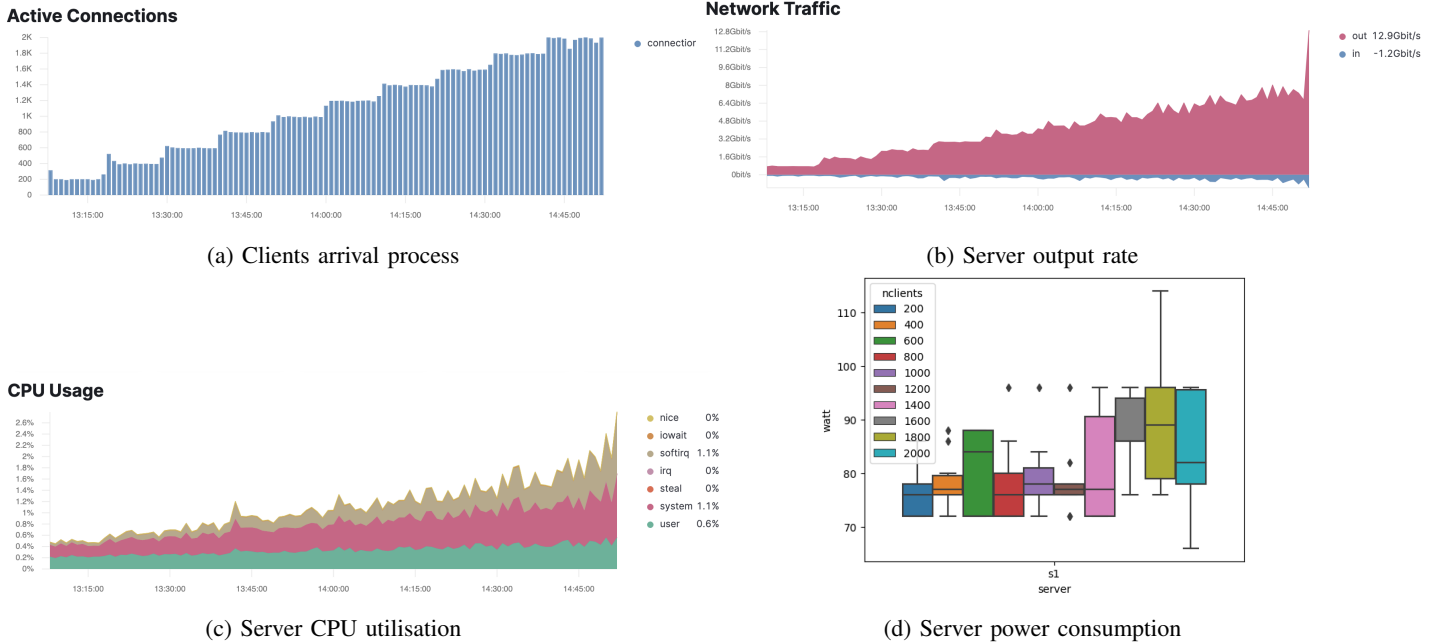


Figure 5: Grid 5000 experiment with one streaming server

user device represent the majority of the cost. The final values are in the range [20,45] grams of CO₂. The smallest estimate comes from the IEA model, which apparently underestimates the networking cost.

The previous results were obtained with the energy factor of France. If we consider an average world scenario, the resulting values will be in range [60,140] grams of CO₂ when scaling the usage phases.

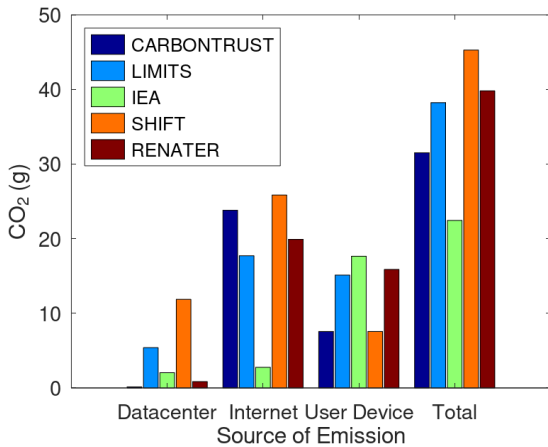


Figure 6: "Aligned" models for (TV,4k,Fixed)

V. STATE OF THE ART

A systematic literature review on the energy consumption and environmental impact of video streaming is done in [2]. It provides an overview of the many factors that affect the

environmental impact of video streaming at different levels: content production, provisioning (encoding, storing, CDN-based distribution), transmission from the cloud to the access network and consumption at the end user equipment. The authors acknowledge the wide range of estimations of CO₂ emissions for one hour of streaming (these estimates include the LIMITS, CARBONTRUST, SHIFT and IEA models) and list potential root causes behind these figures ranging from the difference in carbon intensity among countries or the type of device to the year at which the studied was made.

In [25], the authors present a survey made with over 90 persons in Germany and Austria concerning their video streaming habits in terms of type of streaming service (paid or free platforms), session duration or type of equipment (smartphone or TV). The objective is to combine the information on the user behavior with a LCA approach of a video streaming service to pinpoint the CO₂ emissions with respect to the exact user behavior. Their LCA is based on [17] that was estimating the CO₂ emissions of YouTube in 2016. Overall, the authors in [25] observed that the larger share of impact is due to the paid platforms because of the higher rate combined with a larger screen used, as compared to free platforms.

In [6], the author compares the CO₂ emissions for various social media platforms, including Youtube, Netflix, Facebook and Tiktok. They obtained average CO₂ emissions for the Netflix platform (and the others social media) relying on four models, including the (initial) SHIFT model. They report values between 400 and 1600 g of CO₂ per hour, quite larger than our estimates.

While a bit older, [21] compares, for the US case in 2011, the CO₂ emissions for different means of viewing a video: video streaming, mail or store renting. They report that video

streaming produces an average of 400 g of CO₂ per viewing hour, similar to mail renting but almost 30% more efficient than store renting (because of car usage to reach the store).

[26] reports an LCA of video and audio streaming service in Japan. They account for the production impact of the data center servers as well as the end-of-life phase. An advantage and at the same time a drawback of their approach is that it is specific to the case of Japan. Their results are expressed in kg-CO₂ per MB of data. When excluding the disposal phase and considering a rate of 15.56 Mb/s with a PC and 2.22 Mb/s for a smartphone, one obtains (Table 5 of [26]) 215 g of CO₂ per hour and 15 g of CO₂ per hour respectively. These figures are comparable, though a bit larger, to the estimates: 60 to 140 g for our (TV, 4k, fixed) case.

VI. DISCUSSION

A number of models have been proposed to estimate the carbon footprint of one hour of streaming on the Internet. Our contribution in this work has been to dissect five such models to understand the roots of the observed discrepancies among their results.

We highlighted that these differences stem mostly from (i) the energy efficiency value of the network tier (core network and fixed or mobile access) and (ii) whether the model accounts for the manufacturing cost or not. As for the data center component, most of the models we studied seem to implicitly consider only the cost of the streaming server servicing the client and neglect the complexity of the global streaming architecture in terms of storage server, distribution servers and cache servers. A difficulty is that the architecture depends on the exact streaming service provider as well as the country we consider as each country as its own energy factor. In addition, in a number of cases the streaming server and the clients might not be located in the same country. These questions are fundamental to be able to ultimately obtain estimates of the global streaming activity on the Internet.

As future work, we would like to extend the models under study so that they all be able to account for a mobile access network. This would enable us to consider different types of streaming service, typically a high quality service like Netflix, leading to high data rates and large screen devices; and a large user generated content (UGC) platform like YouTube where the encoding quality is lower because smartphones are used on a mobile access network but the number of simultaneous streams is way larger. Taking into account different deployment strategies, e.g. relying on a dedicated data center or in contrast relying on a third party provider offering a cloud and CDN service might also lead to widely different environmental costs.

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