Estimating the greenhouse gas emissions of daily internet traffic of end-users in the Netherlands

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ABSTRACT

This research aims to facilitate the adoption of digital sobriety as a principle of action by providing a comparative analysis of how different types of daily internet traffic contribute to the digital emissions of end users according to the Sustainable Web Design (SWD) model. This study uses a series of internet traffic measurements of different internet services to characterize different categories of digital traffic. The SWD model divides the digital ecosystem into three key segments: data centers, networks, and user devices. The results indicate that video streaming is the most significant contributor to emissions, followed by browsing social networks. Gaming and audio streaming exhibited the lowest emissions, with video streaming producing approximately 15 times the gCO2eq of gaming. Instagram exhibited a higher data consumption than several video streaming services. The results further demonstrate that data consumption is the predominant determinant of greenhouse gas (GHG) emissions within the framework of the Sustainable Web Design (SWD) model. This is attributed to the minimal impact of the carbon intensity of the network and datacenters, which is overshadowed by the substantial carbon intensity associated with end-user devices and embodied emissions.

1 INTRODUCTION

Motivation

The internet is a considerable contributor to global greenhouse gas emissions; an estimated 1.4% of all greenhouse gas (GHG) emissions are caused by the ICT sector [18]. As the environmental costs of such digital technologies have become more apparent, the reduction of environmental impact has become an increasing priority for data center operators due to regulatory pressure such as the European Energy Efficiency Directive [7] as well as economic incentives associated with the lower cost of renewable energy [15]. Leading data center operators such as Google and Amazon have invested in sustainable energy sources to power their infrastructure[11][2].

An independent organization that records such sustainable advancements of data center operators is the Green Web Foundation (GWF), a non-profit organization dedicated to promoting a sustainable and environmentally friendly internet by 2030. The Foundation aims to reduce the reliance of the internet on fossil fuels and increase the use of renewable energy sources for web hosting and other digital services. The GWF certifies providers as "hosted green" by verifying providers' claims of avoiding, reducing, or offsetting the emissions caused by their digital infrastructure [12]. The Foundation maintains the largest dataset of green-certified providers. The proof for these claims must be provided annually to the GWF so that the certificate can be retained.

In recent years, the term "digital sobriety" gained popularity; the ShiftProjects report, "Towards Digital Sobriety" [23] defines this term as the adoption of practices that reduce the environmental footprint of digital technologies, changing from instinctive or compulsive digital use to a more controlled and intentional approach. A critical step in adopting digital sobriety as a principle of action is awareness about the environmental consequences of our digital usage; this research aims to facilitate this awareness by providing a comparative analysis of how different types of internet traffic contribute to the digital emissions of end-users.

Problem statement

Some investigations have already been conducted on specific internet domains such as video streaming, social media, or other internet-related activities. These studies are not readily comparable due to divergent assumptions, methodologies, and incompatible system boundaries. System boundaries define the scope of emissions, such as direct or lifecycle emissions, and the components included, such as user devices, network infrastructure, data centers, or geographic scope. This lack of standardization complicates direct comparisons between studies. In addition, existing studies often overlook the carbon intensity of the infrastructure of individual digital service providers. This key metric can vary widely depending on the energy mix of the power grid on which the infrastructure is based, which varies by region. Also, some data centers operate on a higher proportion of renewable energy than the standard national grid, further contributing to this variability. Another commonly overlooked metric is the proximity of digital services. Accessing a digital service based on a different continent requires more energy for the network infrastructure to transfer the data than a service based in the same country. Furthermore, the date of the study is especially significant in the context of accessing the carbon impacts of the internet. As highlighted by Koomey and Masanet (2021)[17] one of the pitfalls in assessing the carbon impact of the internet is using old data to estimate carbon emissions, as it can result in significant inaccuracies because IT systems and their energy efficiencies evolve very rapidly. More specifically, the energy intensity of data transmission networks has approximately halved every two years since the year 2000[3]. This temporal aspect can be considered to be the main contributor to the observed variability in the results over the years, which has been shown to vary by up to five orders of magnitude over time [6, 14]. As a result, it becomes increasingly difficult to synthesize these disparate pieces of research into a cohesive, accurate, and up-to-date analysis that can be reliably used in decision-making in the context of internet use.

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Related Work

Several studies have sought to quantify the carbon intensity of various internet services, providing insights into the emissions associated with these activities.

The Carbon Trust conducted an in-depth bottom-up investigation in 2021 on the carbon intensity of video streaming. Their findings indicated that streaming video generates 56gCO2eq per hour. User devices drive a significant portion (89%) of these emissions; consequently, bitrate settings were found to have negligible impact. Notably, this study focused exclusively on operational emissions, excluding embodied emissions from equipment manufacturing. Furthermore, it did not account for the use of renewable electricity by data centers and network operators, assuming the standard average energy mix of the European grid instead. However, when considering the Swedish grid, emissions dropped dramatically to 3gCO2eq per hour, while the German grid resulted in higher emissions of 76gCO2eq per hour [5]

In contrast, Batmunkh[4] attempted to combine results from multiple models, leading to significantly higher estimates. Batmunkh's study reported an average carbon footprint of 982.75gCO2eq for one hour of Netflix streaming. Additionally, the study calculated emissions of 164gCO2eq per hour for YouTube and 328gCO2eq per hour for TikTok. These figures are markedly higher than those presented by The Carbon Trust, suggesting discrepancies that may arise from assumptions made in the respective analyses. However, the calculation methods resulting in significant variability in these figures cast doubt on their accuracy.

An experiment carried out by Greenspector[13] investigated the greenhouse gas (GHG) emissions associated with the top 10 popular social media apps. Their methodology involved creating "User Paths", which are detailed measurement plans, and assessing the device's energy consumption while executing each plan for the respective apps. The study reported emissions of 52 gCO2eq per hour for YouTube and Instagram, 57 gCO2eq per hour for TikTok, and 55 gCO2eq per hour for Reddit. They similarly used this methodology to measure the emissions of commerce and videoconferencing services, among other categories. Although the specific results of Greenspector's study are not directly relevant, as this experiment applied a much narrower scope by only measuring the operational emissions associated with the end-user device, their "User Path" methodology inspired some of the methods of this study.

The Sustainable Web Design (SWD) model is a framework developed to estimate digital emissions. It has been adopted by multiple online emission calculators. The fourth version of the SWD model, published in 2024, categorizes emissions into three distinct segments, as shown in Table1.

Segment	**Energy intensity of Operational Emissions**	**Energy intensity of Embodied Emissions**
Datacentre usage	0.055 kWh/GB	0.012 kWh/GB
Network transfer	0.059 kWh/GB	0.013 kWh/GB
End-user device usage	0.080kWh/GB	0.081kWh/GB
Sum	0.194kWh/GB (68%)	0.093kWh/GB (32%)

Table 1: Energy intensity based on the Sustainable Web Design model [22]

Research Question

This research aims to understand the contribution of various types of internet traffic associated with daily online activities to greenhouse gas (GHG) emissions. Specifically, it addresses the research question: **"How do different types of daily internet traffic contribute to greenhouse gas emissions in the context of Dutch end-users according to the SWD model?"**In examining this question, the study aims to comprehensively analyze the environmental impact of internet usage patterns among Dutch end-users. This will involve assessing the sustainability of various services to represent different categories of internet traffic by simulating realistic usage patterns and considering the variability in network infrastructure. The SWD model will be used as the analytical framework. To use the SWD model effectively, it is crucial to accurately determine the key input metrics, which leads to the subquestion:

- "How do different types of internet services vary in terms of data consumption?"
- "How do different types of internet services vary in terms of carbon intensity?"

In this paper, the methodology will be examined, detailing the approach and calculation methods utilized. Subsequently, the results will be presented along with an analysis. This will be followed by a discussion comparing the findings with those of other studies and addressing the study's limitations. Finally, the paper will conclude with a summary and provide recommendations for future research.

2 METHODOLOGY

Approach

This study uses a series of internet traffic measurements of different internet services to characterize different categories of internet traffic. The routes to the accessed hosts were traced and each hop along the route was geolocated. Then, it is determined whether the node is "green" by utilizing a data set that has been provided by the GWF. This dataset contains a list of certified green providers and their autonomous system (AS) numbers; this information is combined with energy mix and carbon intensity data from Electricity Maps to determine the carbon intensity for each route.

The Sustainable Web Design (SWD) model divides the digital ecosystem into three key segments: data centers, networks, and user devices. Each segment contributes uniquely to the overall greenhouse gas (GHG) emissions from digital products and services. **Data centers** represent the energy required to house and serve data, accounting for 22% of the total system energy consumption. **Networks** encompass the energy used to transfer data across the internet, contributing 24% to the total energy use. **User devices** are the end-user hardware interacting with digital services, consuming 54% of the total energy. Each segment is further

Table 3: Usage Categories for Online Activities

Category	Associated services
Browse social networks	Instagram, Reddit, Facebook
Browse websites	BBC News, Wikipedia, Amazon
Streaming audio	Spotify, Youtube Music
Streaming video	Youtube, Netflix, Twitch
Online Gaming	Fortnite, Dota 2

dissected into operational and embodied emissions. Operational emissions are those arising from the use of the devices in each segment, while embodied emissions stem from their production. For instance, in data centers and networks, operational emissions constitute 82% of the total emissions, with the remaining 18% being embodied. Conversely, user devices have a near-equal split, with operational emissions at 49% and embodied emissions at 51%. This detailed segmentation allows the SWD model to provide a comprehensive estimation of GHG emissions, highlighting the significant use of energy across different stages and components of digital services.

Data centers	Networks	User devices
22%	24%	54%

Table 2: Allocated energy based on the Sustainable Web Design model [22]

Each segment is also divided into **embodied** and **operational** emissions. Embodied emissions refer to the emissions produced during the manufacturing process of the segments mentioned above, and operational emissions refer to the emissions associated with the instantaneous use of the service.

Categories of traffic

Based on the most popular categories of websites and applications [16], five categories 3 were selected for measurement. For each category, 2-3 popular services were selected to effectively represent the category, ensuring a diverse range of services to highlight variations within the category.

For each service, a measurement plan (Appendix A) was devised that is reproducible and close to typical real-world usage. This plan includes a service and a series of tasks to emulate the typical usage of the associated service. This plan is executed for each service while logging all the incoming and outgoing traffic, these measurements are perfomed twice for each service which is then used for further analysis.

Tools

The measurements were manually performed in an isolated Windows 11 virtual environment with all unnecessary background services disabled to prevent interference. Experimentation found that the use of IPv6 reduced the accuracy of geolocating remote hosts due to a less complete IP geolocation database for IPv6 addresses, therefore, it was decided to disable IPv6 and exclusively use IPv4. The Web app browser version was used whenever applicable, and DNS and browser caches were cleared prior to each measurement. Microsoft Network Monitor 4.2 and NetLimiter were used to log the IP addresses accessed by the active process, which were later used to filter the Wireshark capture log. This removed any background traffic that was not relevant to the measurement. Python library Pyshark was utilized to read the Wireshark capture logs, and Scapy was employed to perform traceroutes on each route to determine the intermediate hops. The IP2Location LITE dataset of June 1st 2024 was applied to geolocate each hop and look up its AS number. Then, the AS number was looked up in the GWF dataset, which was provided in consultation with the Foundation; this dataset of May 17th, 2024 and includes a list of 387 certified green autonomous system (AS) numbers. Lastly, data from ElectricityMaps were used to look up the energy mix and the carbon intensity of the electrical grid.

Method of calculation

Four key metrics go into the estimation of GHG emissions.

Energy Intensity: Energy intensity is a constant metric that represents the energy required to transfer 1 gigabyte of data (kWh/GB). This metric exhibits significant variability across different studies, often differing by several orders of magnitude [3]. The primary factors contributing to this variation are the differing system boundaries and the advancements in hardware efficiency. The energy intensity figures of the SWDv4 model were chosen. This choice was motivated by the fact that the latest version of the model was just published recently during the earlier stages of this study, providing recent and up-to-date figures from 2022, and also because of the comprehensive scope of the model, which covers the system boundaries of this study while also allowing the emissions to be separated into six components. The six figures from the SWDv4 model encompass both embodied and operational energy intensity of each segment (User devices, Network, Datacenter), and the figures are displayed in Table 1.

Data transfer: The amount of data traffic transferred over the network using an internet service. In this paper, we use gigabytes (GB) as the unit of measurement for this metric. This is calculated by summing up all the packet lengths in bytes and converting them to gigabytes.

Hop count: The hop count represents the average number of intermediary nodes that data traverses within the transmission network to reach the target hosts. This metric is derived through the analysis of traceroute results. The traceroute methodology hinges on the Time to Live (TTL) parameter inherent to the IP protocol. The TCP traceroute utility employed in this investigation dispatches 30 TCP packets concurrently, each with incrementally increasing TTL values ranging from 1 to 30, to the target host. Each router along the transmission path decrements the TTL by one and returns an ICMP Time Exceeded message when the TTL reaches zero, thereby facilitating a hop-by-hop mapping of the route. The hop count is defined as the smallest TTL value at which the target host responds. Notably, some routers may not return the ICMP Time Exceeded message, and in instances where the target host fails to respond, the

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hop count is considered to be the highest TTL value for which a response is received, incremented by one. The magnitude of impact of hop count is not defined in the SWD model. In this study, the hop count was added as an extension to the model. This metric was employed as a normalization factor to the network segments emissions, whereby the hop count of each observation was divided by the mean value (12.78 hops) to standardize the hop count, which was subsequently utilized as a multiplier to the carbon intensity in the ensuing analysis. Consequently, a service exhibiting hop counts 20% above the mean results in a 20% increase in emissions for the network segement. This is done to represent the Network segment emissions more accurately under the assumption that the emissions associated with the network segment grow linearly with the network's length.

Carbon intensity: This metric quantifies the equivalent CO2 emissions in grams per kilowatt-hour (gCO2 eq/kWh) of energy consumed. It serves as an indicator of the environmental cleanliness of the energy utilized to power the network. The intensity of carbon is dependent on the energy mix of the electrical grid. For example, in France, nuclear energy results in emissions of 5gCO2 eq/kWh [24], whereas solar energy contributes 30gCO2 eq/kWh [9]. The carbon intensity of identical energy sources can exhibit significant regional variations due to differing technological implementations; for example, solar energy's carbon intensity can range from 8 to 122gCO2 eq/kWh [24]. The estimates accounted for these regional disparities by utilizing the latest regional yearly average carbon intensity figure from the Electricity Maps repository [8], which aggregates data from multiple sources across various global regions. For regions lacking explicitly defined values, the default values provided by Electricity Maps were employed as fallback, as detailed in Table 4.

Energy Source	Category	Carbon Intensity
coal	Fossil	820gCO2eq/kWh
unknown	Fossil	700gCO2eq/kWh
oil	Fossil	650gCO2eq/kWh
gas	Fossil	490gCO2eq/kWh
battery discharge	Renewable	301gCO2eq/kWh
hydro discharge	Renewable	301gCO2eq/kWh
biomass	Renewable	230gCO2eq/kWh
solar	Renewable	45gCO2eq/kWh
geothermal	Renewable	38gCO2eq/kWh
hydro	Renewable	24gCO2eq/kWh
nuclear	Low-Carbon	12gCO2eq/kWh
wind	Renewable	11gCO2eq/kWh

Table 4: Global average carbon intensities[10]

The carbon intensity of each of the segments of the SWD model is determined as follows:

- For the **embodied segments**, the 494gCO2/kWh carbon intensity figure was used as recommended by the SWD model. This is the "world" average figure from the ember CO2 intensity dataset. This is because the manufacturing of almost all digital hardware products relies on a global supply chain. Therefore, it is suggested to use the global average grid intensity value.
- The carbon intensity is computed using a different methodology for the operational segments. The **end-user devices** are assigned the 2023 annual average value of the Netherlands from Electricity Maps[9] which is 304gCO2eq/kWh. This approach is justified by the assumption that the typical Dutch end-user relies on the average electricity grid to power their end-user devices.

The **network segment** represents the average carbon intensity of each intermediate node, while the **datacentre segment** is assigned the carbon intensity of the target node. Each service is associated with multiple routes, and the carbon intensities were weighted by the number of packets routed through these paths to determine the average carbon intensity of a service. To determine the carbon intensity of a node, an analysis of its regional energy mix is conducted, using the annual average values for 2021 provided by Electricity Maps. Subsequently, the Autonomous System (AS) is cross-referenced within the GWF dataset to determine its classification as "green." The specific types of energy utilized by green ASs are not explicitly disclosed; hence, certain assumptions are made regarding the energy mix of nodes associated with green ASs. For nodes **not** classified as green, it is assumed that the standard regionional electricity grid powers them. Conversely, it is assumed that green nodes are powered by 100% of the low-carbon sources of the region they reside in, low-carbon sources refers to renewable and nuclear energy sources. Thus, fossil fuel sources are excluded, and low-carbon sources are normalized to aggregate to 100%. The carbon intensity is then computed by averaging the carbon intensities of each source, employing the energy mix as a weighting factor.

The following equation aggregates the aforementioned metrics to compute the corresponding emissions.

$$OM_{DC} = D \times CI_{DC} \times 0.055kWh/GB$$
$$OM_N = D \times CI_N \times 0.059kWh/GB \times \frac{\text{Hop}}{Hop_{avg}}$$
$$OM_{UD} = D \times 304gCO2eq/kWh \times 0.080kWh/GB$$
$$OE = OM_{DC} + OM_N + OM_{UD}$$
$$EE_{DC} = D \times 0.012kWh/GB \times 494gCO2e/kWh$$
$$EE_N = D \times 0.013kWh/GB \times 494gCO2e/kWh$$
$$EE_{UD} = D \times 0.081kWh/GB \times 494gCO2e/kWh$$
$$EE = EE_{DC} + EE_N + EE_{UD}$$
$$E = OE + EE$$

Symbol	Description
D	Transferred data (in GB)
Hop	Hop count
DC	Data center
N	Network
UD	User device
CI	Carbon Intensity (in gCO2eq/kWh)
EE	Embodied emissions (in gCO2eq)
OE	Operational emissions (in gCO2eq)
E	Total emissions (in gCO2eq)

Table 5: List of symbols and their descriptions

3 RESULTS

Emissions

The findings indicate that video streaming is the most significant contributor to emissions, followed by social network browsing. Gaming and audio streaming exhibited the lowest emissions, with video streaming producing approximately 15 times the gCO2eq of gaming. In particular, Instagram accounted for the highest emissions among the social media services, second behind Twitch. The most significant variation was observed within the browsing category. Simple, lightweight websites like Wikipedia emit substantially less than more complex websites like BBC News and Amazon, which feature numerous images and videos.

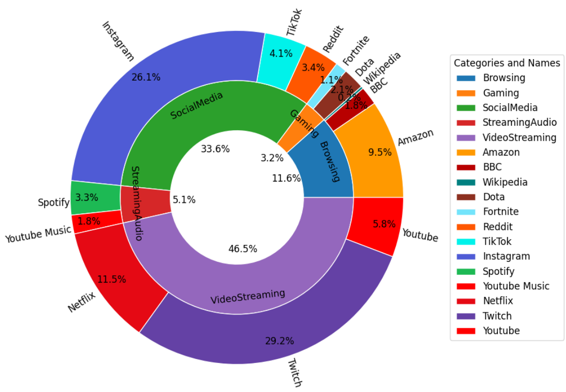

Figure 1: Distribution of network emissions by service and category, normalized by category

The CO2eq emissions of the services exhibited a range from 2 to 264 gCO2eq per hour of usage, with an average value of 67.6 gCO2eq per hour. The standard deviation is notably high at 86.8 gCO2eq , indicating substantial variability in emissions across different services. This pronounced variability can be attributed to the significant differences in data consumption among the analyzed services. The spectrum of emission values implies that while certain services are relatively moderate in terms of CO2eq emissions, others are considerably more intensive. The factors contributing to this variability will be elaborated upon in the subsequent sections. A notable observation is the difference in emissions between Instagram and Twitch; since the two services use the same amount of data, their Embodied and User device emissions are equal. However, Instagram exhibits relatively reduced overall emissions due to its lower network and data center emissions as it has fewer hops and greener network infrastructure.

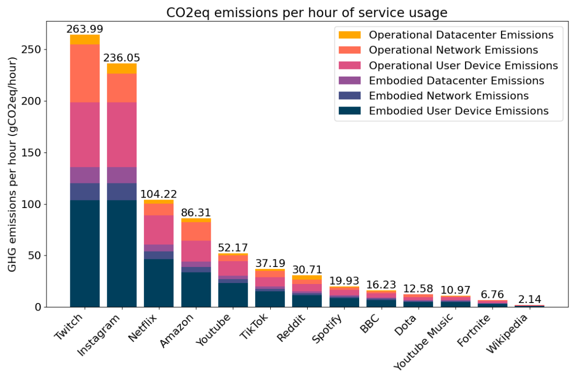

Figure 2: Network emissions by service, according to SWD

Aggregating the above results by category provides insight into the emissions per category. Findings suggest that Video streaming has the highest emissions, and gaming and audio streaming have the lowest.

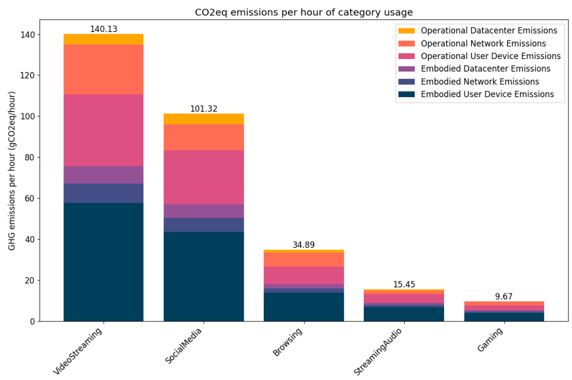

Figure 3: Network emissions by category, according to SWD

Data consumption

Data consumption is closely linked to CO2eq emissions, as it is serving as the only determinant variable for the embodied and user device emissions. Notably, Instagram exhibited higher data consumption than several video streaming services, a finding corroborated by a secondary measurement yielding similar results. This phenomenon can be attributed to the substantial video file sizes, unused pre-fetched media, and high-resolution images prevalent on the platform. Consequently, the emissions associated with data transfer for video services are contingent upon the selected bitrate quality. In this study, the bitrate for Twitch was set at 2.2 Mbit, for Netflix at 1000 kbps, and for YouTube at 0.5 Mbit. Opting for higher bitrate settings for these services would have lead to increased data consumption and consequently higher emission values. For a comparative analysis of the environmental impact of these video streaming services, the carbon intensity data presented in the subsequent section is of particular significance, as it eliminates the bitrate and data consumption as a confounding variable. For Spotify a

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bit rate of 256kbit was configured and for youtube music a bit rate of 128kbps was used, which matches the proportions of the overall data consumption figures.

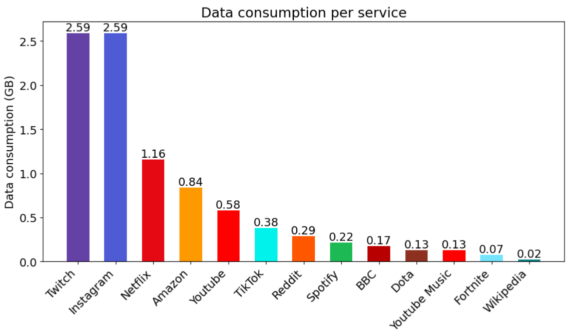

Figure 4: Data consumption of services

Green Certification

For each service, the "Green Percentage", representing the proportion of packets routed through green-certified nodes, was calculated. Instagram exhibited the lowest carbon intensity, followed by Google's services (YouTube and YouTube Music). This is attributed to Facebook's AS 32934 and Google's AS 19527, AS 15169, and AS 36561, all of which are included in the GWF green-certified dataset. Initially, services such as Amazon, Twitch, Wikipedia, and Netflix demonstrated a green percentage below 2% and exhibited the highest carbon intensities. This was primarily due to the frequent utilization of Amazon's AS 16509 and AS 14618, which were not part of the certified dataset, presumably because the reported evidence for these ASes is approximately two years old. However, according to Amazon's 2022 sustainability report, over 90% of the company's energy consumption is renewable [2]. Similarly, Netflix reported 100% renewable energy usage in their 2022 report [20]. Wikipedia's primary AS, AS 14907 operated by the Wikimedia Foundation, was also not certified. Nevertheless, the 2022 Wikimedia Foundation Environmental Sustainability Report disclosed that their data centers are powered by 74% renewable energy, with the remainder being offset through carbon credits. Consequently, Amazon's AS 16509 and AS 14618, Twitch's AS 46489, Netflix's AS 2906, and Wikimedia's AS 14907 were incorporated into the green-certified list, thereby enhancing their performance as depicted in Figure 5. Regarding Reddit, the primary service is hosted on AS 54113 by Fastly Inc., with no evidence of green hosting. Similarly, Dota, which utilizes AS 32590 by Valve Corporation, also lacked green hosting evidence.

The overall carbon intensity did not show much variation since the green percentage only affects the operational network and operational datacenter intensities as constant carbon intensity values were used for the other segments. Note that the carbon intensities of the individual segments in the figures below are weighted by their intensities (Table 1), and the network intensity takes the hop count into account.

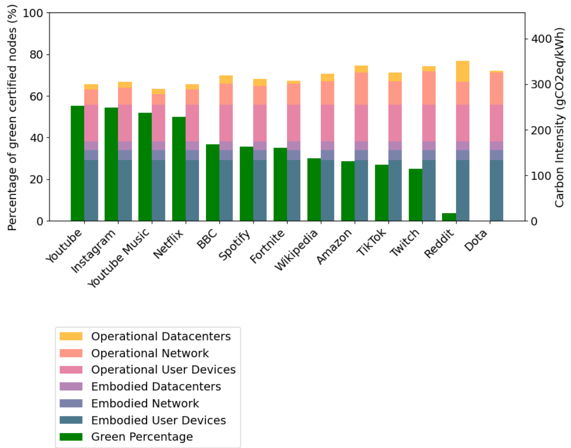

Figure 5: Green Percentage and overall carbon intensity of services

The effects of the "Green Percentage" are clearer when only focusing on the operational network and data center intensities. The data centers have considerably lower intensities than the network. The carbon intensity within the operational network exhibited more variability, attributable to its direct correlation with the 'green percentage.' Services with more packets routed through green nodes generally showed lower intensities, an exception to this was Dota while it was not certified green, its datacenter was running on 25gCO2eq/kWh energy. This is because the primary data center used was located near Stockholm, whose electricity grid runs on 100% low-carbon energy, with nuclear energy being the primary power source [9], In contrast, Reddit's data center was hosted on the Dutch electricity grid, which is much more carbon-intensive.

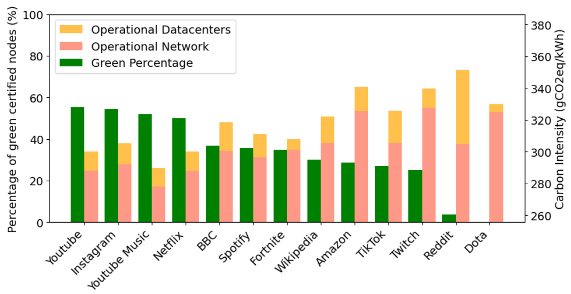

Figure 6: Green Percentage and the operational carbon intensities of network and data center per service

Hop count

The average hop count is 12.78 hops, which is lower than the typical mean value of 15.47 hops [19] indicating these set of services are of close proximity, which is confirmed by the fact that 70% of data are routed within the Netherlands. The low hop count can be due to the Netherlands being a

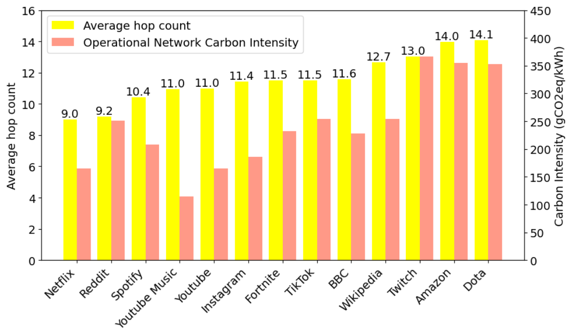

Figure 7: An average hop count of packets and carbon intensity $\times \frac{\textbf{Hop}}{Hop_{avg}}$ per service

global digital hub. Further, the hop count can significantly influence the carbon emissions result. In the measurements, the hop count ranged from a minimum of 9 to a maximum of 14. This variation is attributed to an approximate 56% influence in the carbon emissions for the network segment between the minimum value and the maximum, demonstrating the sensitivity of the emissions calculation to the hop count parameter.

4 DISCUSSION

Compared to related work

The average operational emission figure for video streaming in this study is 64gCO2eq per hour, which is close to the 56gCO2eq per hour reported by the Carbon Trust[5]. This similarity is notable given the differing methodologies employed.

In contrast, the results from Batmunkh[4] show significantly higher emissions and different proportional differences between services. Batmunkh reported Netflix's emissions as six times higher than YouTube's (982.75gCO2eq/hour vs. 164gCO2eq/hour). However, my findings indicate that Netflix's emissions are about double those of YouTube (52gCO2eq/hour vs. 104gCO2eq/hour). This discrepancy is puzzling, given that both studies use models based on a kWh/GB energy intensity principle.

Greenspector's experiment on operational user device emissions reported 52gCO2eq per hour for Instagram, close to the 63gCO2eq per hour found in this study. However, their figures for other services differ significantly. Greenspector reported 55, 57, and 52gCO2eq per hour for Reddit, TikTok, and YouTube, respectively, while this study found 7, 9, and 14gCO2eq per hour. Greenspector's figures are likely more accurate, as the SWD model is based on a kWh/GB energy intensity figure. However, the Carbon Trust report also highlighted that the energy consumption of end-user devices does not increase significantly with increased data transfer[5].

4.1 limitations

This study has several limitations. Firstly, the GWF dataset is incomplete. While the green status of primary destination nodes was verified manually, determining the status of 720 unique intermediate nodes was infeasible, possibly resulting in more green-hosted nodes than the 755 identified.

Secondly, IPv6 was disabled due to reduced IP location database accuracy for IPv6. Akamai reports that 39% of connections in the Netherlands use IPv6[1], potentially affecting the results.

Thirdly, the study did not account for varying energy intensities of different services, as these figures are unavailable and require further research. Energy intensity can vary by user device and data center computational demands, which were outside the scope of the SWD model.

5 CONCLUSION

To answer the study's central question: **"How do different types of daily internet traffic contribute to GHG emissions in the context of Dutch end-users according to the SWD model?"**. Data consumption seems to be the dominant determinant for the emissions of internet traffic according to the chosen model, which can vary widely between different services. Generally, high data-density categories, such as video streaming, emit the most CO2eq, while less data-intensive categories, such as gaming or audio streaming, emit less. The average emissions of 1 hour of internet activity is 67.6 gCO2eq/hour. To put this figure into perspective, 1 hour of average internet traffic is equivalent to tailpipe emissions of driving approximately 270 meters in a gasoline car.[25], 75 grams of bananas or 0.338 grams of lamb meat [21]. The carbon intensity of the traffic is predominantly determined by the embodied and user devices' carbon intensities; however, reducing the carbon intensity of the network infrastructure and data center by using low-carbon energy sources can reduce emissions to some degree. However, there is little more to gain for datacenters that are running on low-carbon sources already. There is still a lot left to achieve in reducing carbon emissions in the network infrastructure and end-user devices.

6 RECOMMENDATIONS

Future research should include a broader range of measurements and internet services to improve the accuracy of estimating internet usage-related greenhouse gas emissions. Incorporating diverse services and usage patterns will provide a more representative picture of emissions.

Additionally, analyzing each service's variable energy intensity can highlight which digital services are more energy-intensive, such as gaming versus music streaming. Using multiple models to compare results can improve reliability by identifying consistencies and discrepancies.

Analyzing daily internet traffic's contribution to greenhouse gas emissions across various geographical locations and comparing these to Dutch end-users can reveal geographical differences and global environmental impacts. Integrating data on the typical time users spend on different internet services would allow for a more precise determination of average emissions over specific periods, revealing variations in digital emissions.

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USE OF AI TOOLS

During the preparation of this work, the author used Writefull, Grammarly, and ChatGPT to rephrase certain parts of the text for improved readability. After using these tools and services, the author reviewed and edited the content as needed and assumed full responsibility for the content of the work.

REFERENCES

[1] Akamai. 2024. IPv6 Adoption Visualizations. https://www.akamai.com/internet-station/cyber-attacks/state-of-the-internet-report/ipv6-adoption-visualization

[2] Amazon. 2022. *Building a Better Future Together 2022 Amazon Sustainability Report.* Technical Report.

[3] Joshua Aslan, Kieren Mayers, Jonathan G. Koomey, and Chris France. 2018. Electricity intensity of internet data transmission untangling the estimates. *Journal of Industrial Ecology* 22, 4 (2018), 785–798. https://doi.org/10.1111/JIEC.12630 Publisher: Blackwell Publishing.

[4] Altanshagai Batmunkh. 2022. Carbon Footprint of The Most Popular Social Media Platforms. *Sustainability* 14, 4 (Jan. 2022), 2195. https://doi.org/10.3390/su14042195 Number: 4 Publisher: Multidisciplinary Digital Publishing Institute.

[5] Carbon Trust. 2021. Carbon impact of video streaming. https://www.carbontrust.com/our-work-and-impact/guides-reports-and-tools/carbon-impact-of-video-streaming Publication Title: The Carbon Trust.

[6] Vlad C. Coroama and Lorenz M. Hilty. 2014. Assessing Internet energy intensity: A review of methods and results. *Environmental Impact Assessment Review* 45 (Feb. 2014), 63–68. https://doi.org/10.1016/J.EIAR.2013.12.004 Publisher: Elsevier.

[7] Directorate-General for Energy. 2024. Commission adopts EU-wide scheme for rating sustainability of data centres - European Commission. https://energy.ec.europa.eu/news/commission-adopts-eu-wide-scheme-rating-sustainability-data-centres-2024-03-15_en

[8] Electricity Maps. 2024. electricitymaps-contrib open source github repository. https://github.com/electricitymaps/electricitymaps-contrib/tree/master/config/zones

[9] Electricity Maps. 2024. Live 24/7 CO2 emissions of electricity consumption. http://electricitymap.tmrow.co

[10] Electricity Maps. 2024. Methodology. https://www.electricitymaps.com/methodology#carbon-intensity-and-emission-factors

[11] Google. 2023. *Environmental Report - Google Sustainability.* Technical Report. https://sustainability.google/reports/google-2023-environmental-report/

[12] Green Web Foundation. 2024. Verification. https://www.thegreenwebfoundation.org/tools/green-web-dataset/get-verified/

[13] Greenspector. 2023. What is the environmental footprint of social networking applications? 2023 Edition. https://greenspector.com/en/what-is-the-environmental-footprint-of-social-networking-applications-2023/

[14] Tom Greenwood. 2020. Why do estimates for internet energy consumption vary so drastically? https://www.wholegraindigital.com/blog/website-energy-consumption/

[15] International Renewable Energy Agency. 2022. Renewable Power Generation Costs in 2021. International Renewable Energy Agency, IRENA. https://app.knovel.com/hotlink/pdf/id:kt0135OI65/renewable-power-generation/latest-cost-trends Section: 1. Latest Cost Trends.

[16] Simon Kemp. 2024. Digital 2024: Global Overview Report — DataReportal – Global Digital Insights. https://datareportal.com/reports/digital-2024-global-overview-report

[17] Jonathan Koomey and Eric Masanet. 2021. Does not compute: Avoiding pitfalls assessing the Internet's energy and carbon impacts. *Joule* 5, 7 (July 2021), 1625–1628. https://doi.org/10.1016/j.joule.2021.05.007 Publisher: Cell Press.

[18] Jens Malmodin, Nina Lovehagen, Pernilla Bergmark, and Dag Lundén. 2023. ICT Sector Electricity Consumption and Greenhouse Gas Emissions – 2020 Outcome. *SSRN Electronic Journal* (Jan. 2023). https://doi.org/10.2139/ssrn.4424264

[19] Ayman Mukaddam and Imad H. Elhajj. 2011. Hop count variability. In *2011 International Conference for Internet Technology and Secured Transactions.* 240–244.

[20] Netflix. 2022. ESG Report. https://about.netflix.com/news/2022-esg-report

[21] J. Poore and T. Nemecek. 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360, 6392 (June 2018), 987–992. https://doi.org/10.1126/science.aaq0216

[22] Sustainable Web Design. 2024. Estimating Digital Emissions. https://sustainablewebdesign.org/calculating-digital-emissions/

[23] The Shift Project. 2019. *Lean ICT: Towards Digital Sobriety.* Technical Report. https://theshiftproject.org/en/article/lean-ict-our-new-report/

[24] United Nations Economic Commission for Europe. 2022. *Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources.* United Nations. https://doi.org/10.18356/9789210014854

[25] U.S. Environmental Protection Agency (EPA). 2023. *Tailpipe Greenhouse Gas Emissions from a Typical Passenger Vehicle.* Technical Report.

A APPENDIX

Time Slot	Application/Website	Specific Task
Browsing Social Media		
00:00 - 00:20	Instagram	Scroll through reels for 20 minutes, fully view each video.
00:20 - 00:40	Reddit	View 20 top threads on r/popular. Spend an average of 1 minute on each thread, fully viewing any videos.
00:40 - 01:00’	Tikto’	Scroll through the ’For you’ page for 20 minutes, fully viewing each video.
Browsing Websites		
00:00 - 00:20	BBC News	Navigate through 5 different sections, select and read one article in each.
00:20 - 00:40	Wikipedia	Skim through articles using the "Random article" feature.
00:40 - 01:00	Amazon	Browse through 4 categories, view ten items each, add five items to the cart, and proceed to checkout.
Streaming Audio		
00:00 - 00:30	Spotify	Listen to 15 minutes of continuous music playback and 15 minutes of an hour-long podcast episode.
00:30 - 01:00	Apple Music	Listen to 15 minutes of continuous music playback and 15 minutes of an hour-long podcast episode.
Streaming Video		
00:00 - 00:20	YouTube	Watch a 20 minute video on 1080p.
00:20 - 00:40	Netflix	Watch a 20 minute episode on 1080p quality.
00:40 - 01:00	Twitch	Watch a live stream for 20 minutes in 1080p.
Online Gaming		
00:00 - 00:30	Fortnite	Continuous gameplay in a standard 100-player match.
00:30 - 01:00	Dota2	Play a 30 minute 10-player match.

Table 6: Appendix A: Measurement plan per category

name	total emissions	operational datacenter emissions	operational network emissions	operational userdevice emissions	embodied datacenter emissions	embodied network emissions	embodied userdevice emissions
Amazon	86.309038	3.958678	17.934607	20.429178	4.979612	5.394580	33.612382
BBC	16.232048	0.771098	2.312658	4.169924	1.016419	1.101121	6.860829
Wikipedia	2.137837	0.089358	0.345140	0.540206	0.131675	0.142648	0.888808
Dota	12.575009	0.187133	2.646543	3.089422	0.753047	0.815800	5.083064
Fortnite	6.764483	0.153377	0.987986	1.783349	0.434691	0.470915	2.934166
Reddit	30.714423	4.117056	4.359004	7.052801	1.719120	1.862380	11.604061
TikTok	37.186090	2.344035	5.728012	9.233393	2.250640	2.438193	15.191818
Netflix	104.220941	4.173619	11.251268	28.161286	6.864313	7.436340	46.334116
Twitch	263.993700	9.381124	55.997790	62.989823	15.353769	16.633250	103.637944
Youtube	52.174518	2.082073	5.712097	14.075036	3.430790	3.716689	23.157832
Spotify	19.930120	0.731554	2.659501	5.245293	1.278540	1.385085	8.630147
Youtube Music	10.968835	0.446065	0.823923	3.075948	0.749762	0.812242	5.060895
Instagram	236.045038	9.581221	27.925617	62.965534	15.347849	16.626836	103.597980

Table 7: Appendix B: Emission figures per service in gCO2eq