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CO2 and its impact: a quantitative study

[Document subtitle]

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# Abbreviations

|  |  |
| --- | --- |
| TWh | Terawatt-hour |
| MMT | Million Metric Tonnes |
| IEA | International Energy Agency |
| EPA | (US) Environmental Protection Agency |
| WRI | World Resources Institute |
| KWg | Kilowatt-hour per GB |
| TLD | Top-level Domain |

# Abstract

[abstract body]

# Introduction

Awareness towards the threat of climate change has increased in the in the last years[[ref](https://climatecommunication.yale.edu/publications/climate-change-in-the-american-mind-december-2018/%20)]. Sustainability, a practice concerned with the recognition of the finite nature of resources, and their conscious usage with regards to future generations has also experienced a similar increase in recognition[[ref](https://www.epa.gov/sustainability/learn-about-sustainability)]. As a result of this growing interest, there has been a larger amount of CO2-related scientific publications published in the past years[[Fabbrizzi et al. 2016](https://www.researchgate.net/publication/295841100_Sustainability_and_Food_A_Text_Analysis_of_the_Scientific_Literature)].

Along with the rise in climate change related concerns, there has also been a growth in global Internet data traffic. In the year 2020 alone ([PCH ref](https://www.pch.net/ixp/summary_growth_by_country)) web traffic exchange has expanded with an average of 40% in size, and has been previously predicted to experience further expansion with close to five and a half billion internet users expected by 2023. ([Cisco 2018](https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html)) This explosion in traffic growth is driven partially by the Coronavirus 2020 pandemic but also by the consistent increases in usage of Internet-connected devices from 2011 onward ([Ericsson 2021](https://www.ericsson.com/4ad7e9/assets/local/reports-papers/mobility-report/documents/2021/ericsson-mobility-report-november-2021.pdf), p. 3), and it is mostly caused by video streaming, conferencing, online gaming and social networking([IEA 2021](https://www.iea.org/reports/data-centres-and-data-transmission-networks)). Device adoption rates vary widely per region though it is estimated that in 2018 the average United States citizen owned about 10 Internet connection-capable devices and consumes 140 gigabytes of data per month ([The Shift Project 2019, 61](https://theshiftproject.org/wp-content/uploads/2019/03/Lean-ICT-Report_The-Shift-Project_2019.pdf))

As these devices become more and more of a central point in human lives the Internet usage grows rapidly as well. 92% of internet users nowadays access the web with mobile phones. ([Statista 2022](https://www.statista.com/statistics/1289755/internet-access-by-device-worldwide/)) Because of this growth the amount of site hits increases with each year and that, in turn leads to a collective increase in overall data consumption ([United Nations 2019, XV](https://unctad.org/system/files/official-document/der2019_en.pdf)).

Data centers are the backbone of website accessibility and they consume around 1% of global electricity use ([Mansanet 2020](https://datacenters.lbl.gov/sites/default/files/Masanet_et_al_Science_2020.full_.pdf)). They are estimated to use around 200-250 TWh of electricity per year ([IEA 2021](https://www.iea.org/reports/data-centres-and-data-transmission-networks)). In general, the usage has fallen “by a factor of four” due to improvements in hardware efficiency.([Mansanet 2020](https://datacenters.lbl.gov/sites/default/files/Masanet_et_al_Science_2020.full_.pdf)).

About the split of electricity usage between data centers and devices.

All of these have one thing in common: they generate CO2.

CO2 emissions have been growing rapidly for more than a hundred years. In the early 1900s they have been estimated to have been around 1000 MMT of carbon dioxide. In the 2010s these numbers reached almost 10,000 MMT ([EPA 2022](https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#:~:text=Global%20carbon%20emissions%20from%20fossil,increase%20from%201970%20to%202011.)). This growth has been driven by a variety of factors: increased globalization, fossil fuel usage, population increase and more ([Climate.gov](https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide#:~:text=Carbon%20dioxide%20concentrations%20are%20rising,people%20are%20burning%20for%20energy.)). Numerous attempts have been made to decrease these emissions, from the Paris Agreement to public awareness campaigns and government reforms([ref](https://www.gov.uk/government/publications/net-zero-strategy)) ([WRI 2019](https://www.wri.org/insights/which-countries-have-long-term-strategies-reduce-emissions) ref 2). The IT sector alone amounts to 1.4% of global emissions but it can be reduced to below 20% of that if a switch to renewables were to happen ([Ericsson 2020](https://www.ericsson.com/4907a4/assets/local/reports-papers/consumerlab/reports/2020/ericsson-true-or-false-report-screen.pdf)).

(Will need to add something about the type of energy used)

There has been research made about the IT sector’s emission generation but none of them have attempted to analyze the web’s CO2 footprint. In this thesis, an attempt will be made to create a clear overview of some of the web’s most popular websites and their CO2 generation footprint.

To do so, the following research question will be addressed:

*What is the current state of energy consumption of Web sites?*

## Thesis Structure

In the next chapter the [ ] is defined. Chapter 3 talks about [ ] and Chapter [ ] is about [ ]. In the last chapter an answer to the research questions will be provided and suggestions for further research as well.

# Related Studies

Several separate studies have analyzed the electricity consumption of the average Internet data transfer, for various devices (Weber et al. 2010; Hinton et al. 2011; Kilper et al. 2011; Lanzisera et al. 2012). Here, estimate comparisons are difficult to do because of inconsistent usage of methodologies and data uncertainty. Some, are based on either estimates of regional or of worldwide energy consumption while on the web, combined with traffic estimates to compute the amount of energy consumed per some data amount. Other studies model the network components needed to provide the Internet traffic for a known subscriber amount. The distinction with the largest influence on the result, however, is the definition of system boundaries. Though some studies include the terminal equipment (e.g., personal computers and servers) within the system boundaries (Koomey et al. 2004; Taylor and Koomey 2008; Weber et al. 2010), others do not (Baliga et al. 2007, 2008,2009; Hinton et al. 2011; Kilper et al. 2011). Most studies include the overhead for cooling and power distribution, but Lanzisera and colleagues (2012) do not. Because of these differences and of an lack of access to more modern data, I do not undertake a comparison of such statistics here. Instead, there is a focus on a data which is particularly well characterized and the system boundaries clear and consistent. Some, newer industry studies on the energy consumption of both cloud and traditional computing provide insight on the energy consumption induced by network traffic. [study here]

# Research Method

The purpose of this chapter is to explain the research methods used in this paper.

## Methodology

To write this paper, books, academic articles, journals, reports, and statistical analyses have been used. Additionally, the data used has been collected from several sources: Website Carbon’s API, [list other sites].

The data analysis will be strictly quantitative. The goal here is to analyze the impact of our internet surfing habits on a relatively large scale and to compare an innocuous habit with the real-world impact it has. Due to the nature of the service that the data is sourced from, the analysis will be done entirely on the homepage of a given website and because of that there will be no focus on analysis of other types of data transfer like streaming video from a particular streaming service, loading multiple pages from the same website or infinitely scrolling pages (e.g., Twitter, Facebook, NBCNews.com).

The main data has been collected by using the Website Carbon API. It is an online tool created by Wholegrain Digital that provides an estimate for the amount of CO2 a website generates. It awaits a query in the form of a URL and returns a JSON file containing several statistics about the website.

The dataset where all the statistics have been collected is a .csv file generated from the data retrieved by the aforementioned API. It contains information about the 50,034 most popular websites and it has the following features:

1. Website URL
2. Type of hosting – Depends on the energy source used by the data center. Saved as either ‘True’ for websites hosted by a service provider using green energy or ‘unknown’ for those whose green status could not be determined. The status is determined by the Green Web Foundation’s own API. ([ref](https://www.thegreenwebfoundation.org/)) There, any websites that is hosted by a ‘Green’ data center is shown as using Green energy (Note: Not all centers mentioned on the GWF website use Green energy, in some cases they use standard grid and the emissions are offset afterwards.).
3. Number of bytes – The amount transferred upon the initial page load, provided that the website hasn’t been visited before.
4. Number of bytes (adjusted) – An adjusted value for the second visit of a website which takes into consideration browser caching.
5. Percentage of sites it is cleaner than – A simple comparison between the amount of CO2 the currently tested website generates and the others in the database. Comparison is done at [ ].
6. Energy – The amount transferred upon a single page load, in Kilowatts per Gigabyte.
7. Grams and liters of CO2 transferred for the renewable grid
8. Grams and liters of CO2 for the national grid.

The website list we are using has been sourced from the [Tranco](https://tranco-list.eu/) list of 1 million most popular websites. Tranco is a list which uses averaged data from four other ranking providers (Alexa, Cisco Umbrella, Majestic and Quancast). The data has been [explain Tranco here] ([Pochat et. al. 2019](https://tranco-list.eu/assets/tranco-ndss19.pdf)). The original list was retrieved at 03/05/2022.

The dataset that was used for analysis has been sourced between the period of 04/05/2022 and 21/5/2022.

### Errors and Limitations

The set has been cleaned up of any accidentally repeated data and several manual edits have been made for the following issues:

1. Google redirects: Some URLs (like Google’s regional domains) redirect to the main Google.com domain. This created several hundred duplicate “https://www.google.[region]/” entries. In this case the redirected entries have been removed and only the first one from each region has been kept with the presumption that it is the original one.
2. General regional redirects: The same issue appeared for several other websites and has been dealt with in the same way.

Additionally, the data has been formatted to account for visual clarity and ease of use (decimal sign placement, general formatting).

An occurring issue encountered during this data collection process was also a large number of websites which could not be analyzed for different reasons. These reasons are as follows:

1. The website was offline.
2. The website was hosted by Cloudflare – In this case the API returned a response in an HTML form and not JSON. Each time that happens the corresponding website is skipped.

A few other reasons, as mentioned by Wholegrain Digital on their website. Those are:

1. The website can be accessed by the public through a standard web browser.
2. It does not require login.
3. It allows search engines.
4. Contains unique content aimed at human visitors – this excludes holding pages, error pages, server notification pages, demo pages or pages that are generally useless (this is highly subjective).
5. Is free from illegal or explicit content.

The original goal of the project was to parse the entire one million website list. Unfortunately, another limitation was encountered at the data collection process: the API used has a daily limit of 25,000 hits available to it. The API is also shared with other users and because of that the number of sites that could be parsed per day was no more than two to three thousand.

Overall, the first 65,600 websites from the Tranco list were parsed. 52,431 of those were parsable and after the removal of any duplicates there were 50,034 usable websites. The loss from the parsed to parsable is 21.1% and from parsable to usable is an additional 4.6%.

## Software

The research question and the scope of the paper were defined in the previous sections. Here, the tools used for the data collection process are described.

There were two main methods used:

* An HTTP Request/Response program (async\_alternate.py) which main function is to send out asynchronous requests to the Website Carbon API and receives JSON formatted responses in return. It has been written with Python 3.10.4 64bit.

Additionally, these libraries were used:

1. ASYNCIO ([Python.org](https://docs.python.org/3/library/asyncio.html)). Part of the Python Standard Library. Utilizes concurrent programming concepts to make asynchronous programming possible. It is used because asynchronous requests fare multiple times faster than sequentially programmed ones, depending on the implementation and the receiving server’s limitations. [detailed explanation about concurrency)
2. AIOHTTP ([Documentation](https://docs.aiohttp.org/en/stable/)). Written by Nikolay Kim and Andrew Svetlov. A client/server library that utilizes ASYNCIO for making asynchronous HTTP GET requests targeted towards a public endpoint from the Website Carbon API.
3. Throttler 1.2.1 ([Documentation](https://pypi.org/project/throttler/)). Used for throttling the amount of outgoing GET requests, as to not overload the receiving server.

* The Website Carbon API which provides the data to the Python program.

# Calculations/API Description

The amount of emissions generated by a webpage are calculated with the following factors:

1. Data transfer over the wire – the amount of data that is transferred from the server to the user upon a page load.
2. Energy intensity of web data – The amount of energy used to load a page.
3. Energy source used by the data center – can be either True or False. True represents the energy used by the data center coming from green sources, False means standard energy. This is checked through the Green Web Foundation database.
4. Carbon intensity of electricity – Carbon intensity is the amount of carbon dioxide generated to create a unit of electricity.( <https://www.nationalgrideso.com/future-energy/net-zero-explained/what-carbon-intensity>) Usually measured in grams of CO2 per kilowatt-hour. Here it is based on the international average for grid electricity.
5. Website traffic – The number of page views on a website.

The API uses a number of formulas to make the exact calculations. They work as follows [(Sustainable Web Design 2022](https://sustainablewebdesign.org/calculating-digital-emissions/)):

### Energy per visit in kWh (E):

E = [Data Transfer per Visit (new visitors) in GB x 0.81 kWh/GB x 0.75] + [Data Transfer per Visit (returning visitors) in GB x 0.81 kWh/GB x 0.25 x 0.02]

### Emissions per visit in grams CO2e (C):

C = E x 442 g/kWh (or alternative/region-specific carbon factor)

### Annual energy in kWh (AE):

AE = E x Monthly Visitors x 12

### Annual emissions in grams CO2e (AC):

AC = C x Monthly Visitors x 12

### Annual Segment Energy:

Consumer device energy = AE x 0.52

Network energy = AE x 0.14

Data center energy = AE x 0.15

Production energy = AE x 0.19

### Annual Segment Emissions:

Consumer device emissions = AC x 0.52

Network emissions = AC x 0.14

Data center emission = AC x 0.15

Production emission = AC x 0.19

# Data Analysis & Results

It can start with tables showing the amount of data I’m working with.

Then there will be a structured analysis, on a few major categories and subcategories.

Show:

Mode / Median / average co2 generation

bytes / adjusted bytes proportions

min / max of co2 / bytes

frequency of co2 / bytes in groups

## General Analysis

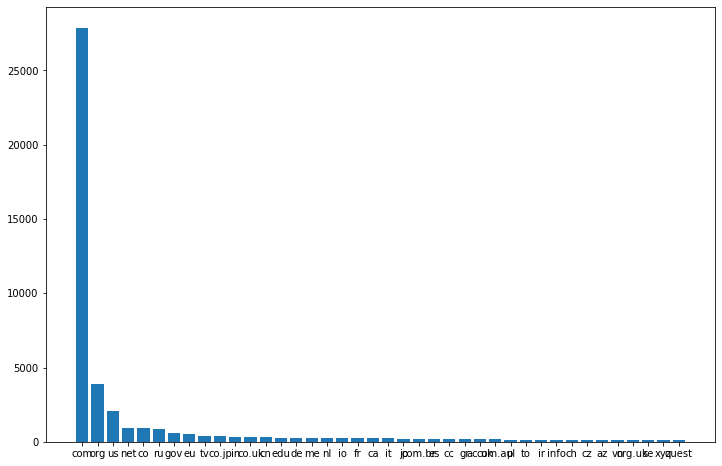
### Overview

#### Dataset Distribution

To provide a sound picture of websites and their CO2 emission impact, more than 65 thousand websites were overall analyzed. All websites were sourced from the original Tranco list and there were no distinctions done to the website’s importance during the data collection process, they were all collected in the original order of popularity.

Top-Level Domains: There are 50,034 usable websites in the final dataset. From those, 27,873 have the “.com” top-level domain, 3868 have “.org “, and 2065 have “.net “ as the domain. Full distribution follows in the table snippet below. Overall, there are 716 different top-level domains [full table appendix]. Keeping only those which occur more than 100 times leaves us with exactly 40 domains. The distribution is heavily skewed towards the first 3 TLD’s which account for 67.5% of the entire dataset.

Figure 5: TLD Distribution



Website Sizes: A website’s size affects the time it will take to load it and the amount of CO2 it will generate. The collected websites vary greatly in range. The smallest one is 168 bytes and the largest one is <https://www.lematin.ma/> at 304MB. These are only outliers though as the mean size is only 3.69MB and the unaffected by outliers median stands at 2.23MB. Overall, all the websites take 184.93GB of space.

A webpage has two different sizes registered under it. One, under the column ‘Bytes’, contains the amount the server transfers upon the initial page load, and the second one, under the ‘Statistics: CO2’ column is the amount transferred on a second page load, with caching taken into account.

#### CO2 Distribution

On average, a site generates 0.562 grams of CO2 per first page load. The minimum amount registered is 0.000042 but the largest one is much bigger, at 76 grams per load.

## Outliers

One of the first interesting things noticed after the inspection of the dataset in both by histograms and manually was the presence of outliers in the data. Outliers are defined in differing ways in statistical literature. Hawkins (1980 [ref](Hawkins,%20%20D.M.%20%20(1980),%20)) defines an outliers as “an observation that deviates so much from other observations as to arouse suspicion that it was generated by a different mechanism”. On the other hand, Grubbs (1969 [ref](Grubbs,%20%20F.E.%20%20(1969),%20)) states them as “An outlying observation, or outlier, is one that appears to deviate markedly from other members of the sample in which it occurs”. The meaning behind the different definitions is that an outlier is a point of data located much farther from the average than most of the dataset.

Outliers can have a negative impact on a quantitative analysis for a variety of reasons, one of them being that they can influence important estimates in a very negative way. In a general sense, there are two major reasons for the existence of errors in a dataset: human error (wrongly inputted data) or technical error (miscalculation by the system).

Chart, bar chart

Description automatically generatedOutliers come in different types. In data mining, they can be global, collective, contextual and in general statistics they can also be univariate and multivariate. Global outliers are those that “all outside the normal range for an entire dataset” ([Alghushairy 2020](https://www.researchgate.net/profile/Xiaogang-Ma-4/publication/348057855_A_Review_of_Local_Outlier_Factor_Algorithms_for_Outlier_Detection_in_Big_Data_Streams/links/5ff4f2a845851553a0228612/A-Review-of-Local-Outlier-Factor-Algorithms-for-Outlier-Detection-in-Big-Data-Streams.pdf?_sg%5B0%5D=1uWtipqV9qnQtXtc0ZWutfjIPfZrFW9XyAeGivnGhUmB2VEW_DH4IjoFEpXlQqQlEzIKBVG-_ABERNkxN4Q9kA.-QAkGfP0jTKCbqPlZYBJHMpzZGj4aJC3VyfnC1ni1tuyQvIXQqLtBhJRnt8-8y8Vq4m9Vr-wpL8sPb3M2LhnXQ&_sg%5B1%5D=_yQHz9png7WC5bvECX1jJyayM_ZNjQEj9cILwYqFDzmcxyWdHeN_oB2V1iZi1UsXNB-U-G9VPv7HH4utDQZV5QMP1vXovfsolgk4eMYn-bFj.-QAkGfP0jTKCbqPlZYBJHMpzZGj4aJC3VyfnC1ni1tuyQvIXQqLtBhJRnt8-8y8Vq4m9Vr-wpL8sPb3M2LhnXQ&_iepl=)) and univariate outliers are defined as “a case with an extreme value that falls outside the expected population values for a single variable” ([Tabachinck & Fidell 2013](Tabachnick,%20B.%20G.,%20&%20Fidell,%20L.%20S.%20(2013).Using%20multivariatestatistics(6th%20ed.).%20Boston,%20MA:%20Pearson.)). All of the outliers which will be discussed in this section fall in those two categories.

Figure 1: Average, Mean and Standard Deviation for "Bytes"

Understanding the nature of our outliers is important to the nature and validity of the data. What made the outliers occur? Was it human error or a technical one, and what do they say about the websites?

At first look at the dataset, we notice a large difference in website sizes. Looking at the “Bytes” and “Adjusted Bytes” columns we see that although the average website size in “Bytes” stands at 3.69MB, the mean is only 2.23MB, a clear sign of the distribution being off. Looking at the top 10 and bottom 10 values in “Bytes” shows us just how large the difference is.

|  |  |
| --- | --- |
| Top 10 Bytes | Bottom 10 Bytes |
| 304084175 | 168 |
| 221431538 | 170 |
| 174746287 | 185 |
| 173488420 | 200 |
| 158429770 | 207 |
| 153772730 | 209 |
| 144149539 | 209 |
| 131234648 | 218 |
| 110049081 | 227 |
| 103846179 | 230 |

The largest recorded website is 304084175 bytes (304MB) and the smallest only 168 bytes. From the top 10 we see that each website drops off in size from the previous one by anywhere between 5 and more than 80 megabytes and the 10th is “only” 110MB. The bottom ten looks very different with all the websites weighing at less than 1/5th of a megabyte.

So, what is the reason then? After performing tests on a random selection of the outliers a few different patterns are easily observed, but none of them can be called the sole reason for the difference in estimates. In some cases, the reason was simple: the website was offline; thus, the API did not record anything beyond a generic browser response. Others were a blank page, sometimes with a few lines of text, or were not indexable due to the several reasons listed by Website Carbon which I’ve mentioned earlier.

All of these relate to the bottom ten. For the top ten the reason was much more surprising and interesting. It had to do mostly with the page contents not being optimized at all.

Before anything, it bears remembering that some websites are more demanding by nature. Streaming services of course download videos locally often, but news sites on the other hand have a lot of dynamic content which gets updated daily.

The largest website mentioned previously, and one that will serve as a general example is <https://lematin.ma/>, the online version of Le Matin, a Moroccan daily newspaper. This site, tested initially on 15/05/2022 was estimated to be 304MB, as previously stated, but on further testing it returned vastly differing sizes, ranging anywhere from the original estimate, to 11.4MB, as of 10/06/2022. Examining the website with Google Chrome’s Developer ToolA picture containing graphical user interface

Description automatically generateds, caching disabled, no advertisement blocking, and screen resolution forced to 1080p within the browser (to prevent the mobile version from appearing) was done on several different days and it showed that the website is filled with heavily unoptimized images and videos, most of them coming from article previews, automatically scrolling sections and ads. For example, on 27/05/2022 there were two identical ad videos hosted on the website each of them being 84.4MB. On 06/10 again, minutes after the previously mentioned test, the website ballooned from 11.4 to 179 megabytes after an automatically triggered refresh and multiple videos ranging from 5 to 73mb were loaded. Upon further refreshes, none of which were triggered from my side, the size decreased to a “mere” 117MB and 63MB.

Figure 2: An example of the largest files



Figure 3: 06/10/2022, 16:53, LeMatin.ma



Figure 4: 06/10/2022, 16:59, LeMatin.ma

The same essential pattern shows up on many of the large websites in the dataset. Ittefaq.com.bd, a Bangladeshi newspaper exhibited similar size changes, it was initially recorded as being 158MB in both Website Carbon and Chrome Developer Tools, but on 06/10 it only transferred 11.9MB.

The other sites exhibiting those patterns were either sites with heavy graphics like <https://warnerbrosgames.com/> where the heavy content was in the shape of game advertisement videos or adult content streaming services some of which were loading the videos automatically and one particular example even hosted an entire visual novel game on the home page.

These tests were performed at random intervals, and for one reason: to determine whether retesting would be needed to verify the correctness of the data. One important fact about the nature of the outliers has been verified by this, the data is not a product of human or technical error, it truly represents a website’s state at the time of testing and gives clear examples to the importance of proper web development done with respect to standards and quality. [change]

### Top and Bottom 1000

For these two we will look at the general trends, in a similar way to the overview section but we will compare the differences between the entire dataset and the top and bottom, on average. Also, will compare the difference between the top/bottom.

Here we observe similar numbers to the entire dataset. The top 1000

### Hosting Type

We will look at how much of a difference the type of hosting used makes on the emissions. Things that can be looked at are the differences in averages between the two categories here and the proportion of big sites that have green vs unknown hosting. The amount of overly big sites (those that are much bigger than the average).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Green Hosting | Bytes | Statistics: Energy (KWG) | Statistics: Grams of CO2 (Grid) | Statistics: Liters of CO2 (Grid) |
| False | 104068160248 | 59.272054 | 26198.247878 | 14571.46547 |
| True | 80863090299 | 46.055599 | 20356.574757 | 11322.32688 |

## Per Domain

### Original Domains

The original domains are looked at in terms of size, amount of co2 that they contribute to the overall dataset, and it will be shown how many unknown hosting sites every domain has.

### Domain Popularity (Top 20)

Sourced from <https://w3techs.com/technologies/overview/top_level_domain>

Will every category have the same general data in it?

### Other Domains

### Per Regional Domain

For these there will be a few standard measurements shown and they will be compared between each other.

## Per Company

The different companies will be analyzed in a manner similar to the Regional section. Look at which companies say are green friendly and check if their websites are so as well.

Other Ideas: Per category of site (requires paid API)

# Discussion

In order to truly see the impact, a website has on the environment it is necessary to know how the data compares to real world examples. To do so the data will be now compared against measurements sourced from [ ].

First this will be a comparison with CO2 generation by people, cars, etc.

The second part will be an analysis on 1000 downloaded websites and seeing how many of them contain large images.

# Conclusion

# References

Adams, C. et al. (2022) Calculating Digital Emissions, In *Sustainable Web Design,* (Accessed: April, 12 20221) <https://sustainablewebdesign.org/calculating-digital-emissions/>

# Appendices

[notes]

Mention any issues, topics and things to look into for future research