Sustainability in the Digital Age: Assessing the Carbon Footprint of E-Commerce Platforms

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Abstract. Sustainability is one of the development trends of various businesses, including those focused on digital channels. One example of the practical engagement is the care taken to minimize emissions of the various greenhouse gases, e.g. carbon dioxide. While e-commerce does not directly affect emissions, it does consume electricity, the generation of which increases the amount of CO_2 in the atmosphere.

This paper focuses on analyzing the carbon footprint of the top 100 most popular Polish e-shops in order to verify their commitment to sustainability. The research uses a measurement method used in online carbon footprint calculators, which, despite significant simplifications, allows a rough estimate of a website's impact on carbon dioxide emissions. Nevertheless, the perceived limitations of the algorithm used made it possible to suggest directions for its development, which could significantly affect the accuracy of the calculations.

Keywords: E-commerce · Sustainability · User interface · Carbon footprint.

1 Introduction

In an era of digital transformation, e-commerce has become an integral part of everyday life, revolutionizing the way people shop and do business. The convenience and accessibility offered by online storefronts have contributed significantly to the growth of online retail, and e-commerce is projected to take over 41% of global retail sales by 2027 [2]. However, the rapid expansion of the digital market comes with a number of environmental challenges, particularly in terms of carbon emissions. The widespread digitization of life today also has an impact on the environment, both positive and negative. Notable among these is the increase in global greenhouse gas emissions attributable to digitization, which is estimated to be around 4% [17]. One reason is the need to power increasingly large data centers, which are energy-intensive and account for about 1% of global electricity consumption [14].

As consumers increasingly rely on online platforms to meet their shopping needs,

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the environmental impact of e-commerce activities is a growing concern. The energy consumption, transportation logistics, and server infrastructure required to maintain digital marketplaces contribute to greenhouse gas emissions, exacerbating the global climate crisis. While many of these aspects are beyond the control of e-commerce platform owners, they can still take steps to engage their business in environmentally responsible practices. It is critical to understand and mitigate the carbon footprint of e-shops to align digital commerce with broader sustainability goals. The carbon footprint is associated with every stage of the e-commerce lifecycle, from production and distribution to use and disposal. However, from the perspective of an individual e-commerce store, optimizing the site that customers use every day and choosing data centers that use renewable energy are two initial steps that can be taken.
The aim of this paper is to analyze the carbon footprint of a selected group of e-commerce sites and verify the algorithm proposed by the Sustainable Web Design (SWD) community group for calculating the carbon footprint of websites [9]. The methodology used in this research involves the collection and analysis of data from a representative sample of e-shop websites, spanning a variety of industries and business models. One hundred Polish online stores with the highest traffic were selected for the study, as this is the country with the highest carbon dioxide emissions per kWh of energy (835g/kWh in 2023) in Europe [7]. This means that changes made to Polish e-shops can have a much greater impact on the environment than similar changes made to e-shops in countries with much lower CO_2 emissions from electricity production. Such a conclusion is based on an estimate that the end-user devices are responsible for more than 50 percent of the energy consumed in the e-commerce [9]. Well-designed user interfaces can reduce the amount of data transferred and the time it takes to make an online purchase, reducing the environmental impact of using these devices.
The contribution of this paper is threefold. First, it presents the results of a study of the carbon footprint of a selected group of online stores, taking into account how they power the data centers they use. Second, it discusses the assumptions of the carbon footprint calculation algorithm adopted by the SDW community and suggests ways to improve it. Finally, the paper contributes to the discourse on sustainable e-commerce practices and provides insights that can guide the industry towards a greener and more environmentally responsible future.

2 Literature review

In recent years, the rapid growth of e-commerce has significantly changed consumer behavior and business operations. As the digital landscape expands, concerns about its ecological implications have gained prominence. Understanding and mitigating the environmental impact of online shopping is critical to fostering a more sustainable future. One of the most popular directions is the concept of *digital decarbonization* [5]. Reducing the digital carbon footprint should be a critical part of any corporate sustainability strategy, based on the conscious

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reuse of knowledge and data and the promotion of digital best practices to minimize CO_2 emissions from data [13]. But minimizing your online carbon footprint is something everyone can do. Reducing the resolution of a streaming video or turning off the camera during an online conversation can reduce the resulting greenhouse gas emissions by up to 25 times [15].

Digitization can contribute to greenhouse gas emissions in several ways, some of which are directly related to the increased importance of e-commerce in the global economy. The energy used to collect, process, transmit and display information is a primary concern [12]. The quantity of data utilized by individuals is increasing annually. For instance, in 2020, the average European citizen used approximately 187.3 Gigabytes (GB) of data per year, which represents a yearly increase of over 30% and a nearly 300% increase over the course of five years [10]. However, it should be emphasized that the environmental impact of e-commerce is not limited to data transmission. Online stores are just one sales channel in a supply chain that includes manufacturers, suppliers, distributors and end customers. Comprehensive and consistent action is necessary to reduce the carbon footprint at each stage [3]. For example, CO_2 emissions related to online shopping can also be analyzed in terms of the packaging used and its environmental impact [1]. Packaging materials commonly used in standard shipments include wrapping paper, envelopes, cardboard boxes, plastic bags, woven bags, tape, and cushioning materials such as bubble wrap and styrofoam [4]. It is important to consider that some packaging is made from non-renewable materials when making a purchase or selecting a delivery method. Environmentally responsible practices may include the use of packaging made from renewable resources, such as naturally occurring cellulose materials or recycled materials such as paperboard [8]. On the other hand, logistics is undoubtedly crucial, as it accounts for approximately one-fifth of global CO2 emissions [16]. The choice of logistics model [19] can have a significant impact on the final outcome. Finally, it is important to consider artificial intelligence, which is increasingly used in e-commerce, but also has a significant carbon footprint. It is estimated that the ChatGPT tool alone produces 24 kg of *Carbon dioxide equivalent* (CO_2e) per day [11].

Reducing the carbon footprint of an e-commerce store can be a daunting task for business owners. However, a good starting point is to focus on reducing the amount of data sent during a customer visit and using data centers that rely on renewable energy sources.

3 Research on carbon footprint of e-shop websites

3.1 Methodology

The goal of the study was to verify the carbon footprint of TOP100 online stores in Poland with the highest traffic according to Ahref's stats [18].

For the purposes of the study, the assumptions suggested by the Sustainable Web Design community were adopted. The following assumptions were made for the CO_2 footprint calculations:

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- Annual Internet Energy (AIE) = 1988 TWh and Annual End User Traffic (AEUT) = 2444 EB,
- Energy Intensity of Data Transfer (EIDT) = AIE/AEUT = 0.81 [kWh/GB],
- Carbon factor - global grid (CFgg) = 442 [g/kWh],
- Carbon factor - renewable energy source (CFres) = 50 [g/kWh],
- Entering the site requires transmission:
  - 100% of the data the first time,
  - Cache Efficiency (CE) estimated as 2% of the data each time a web page is downloaded, by using the device's cache,
- Returning Customers (RC) make up 25% of the total user base [6],
- Data centers (DCE) accounts for 15% of energy used.

The experimental research involved the following steps:

1. using the Google PageSpeed Insights API to get information about the total amount of traffic on the first visit to the site ($DTpV$ - Data Transfer per Visit),
2. determining whether the data centre used by the site uses renewable energy sources (DCres=1 if so, DCres=0 if not), based on the service available in the Green Web Foundation's API (https://www.thegreenwebfoundation.org/),
3. calculating the carbon footprint of the site.

The following formulas, expanding the SWD concept to include renewable energy sources in powering data centers, were used to calculate the carbon footprint:

$$EpV = DTpV * EIDT * RC + DTpV * EIDT * (1 - RC) * CE$$

where: EpV - Energy per visit [kWh]

$$CO_2e = \begin{cases} EpV * CFgg, & \text{if } DCres = 0 \\ EpV * CFgg * (1 - DCE) + EpV * CFres * DCE, & \text{if } DCres = 1 \end{cases}$$

where: CO_2e - Carbon dioxide equivalent [g]
For each online store studied, the DTpV determination was made for the home page only; sub-pages such as listings, product cards, fixed content were not checked. A detailed examination of these aspects of e-commerce sites will be the subject of future research.

3.2 Results

100 Polish on-line shops were selected for the survey, but 6 of them failed to retrieve information on the amount of data submitted during the first visit. Therefore, the carbon footprint analyses were performed on a set of 94 e-shops. In addition to gathering information about the data being transferred, the datacenter being used was also verified. In this case, three options were possible:

1. standard datacenter,
2. datacenter using renewable energy sources,

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Table 1. Summary of data centers used.

Data center	Quantity	Percentage share	The most popular hosting
Standard	19	20.2%	-
Using renewable energy sources	42	44.7%	Akamai Technologies (18), e24cloud by Beyond (6)
Unknown (proxy)	33	35.1%	Cloudflare (26), Amazon CloudFront (7)

3. reverse proxy, not allowing to determine the actual hosting.

A summary of the data centers used by the analyzed e-shops is shown in Table 1. Due to the fact that there was a significant portion of hostings that could not be directly classified into either group one or group two, and therefore it was not possible to assign a unique value to the $DCres$ parameter, it was necessary to modify the original assumptions regarding the calculation of the CO_2e index value.
The change was the addition of a third variant expression for calculating the value of CO_2e in case it cannot be determined whether the hosting uses renewable energy sources (DCres=2):

$$EpV = EpV * CFgg * (1 - DCE) + EpV * CFunkn * DCE,$$

The $CFunkn$ value was calculated based on the $CFgg$ and $CFres$ values and the proportion of standard (31,1%) and "green" (68,9%) hosting among the e-stores included in the survey.

$$CFunkn = 0,311 * CFgg + 0,689 * CFres = 172,10[g/kWh]$$

Taking into account the above modification, it was possible to calculate CO_2e values for 94 e-stores. The lowest index value was recorded for Bonito's online store, while the highest value was recorded for Agata Meble's store.
It can be observed that the CO_2e value increases linearly for most e-commerce sites, but the results change sharply for about 10% of the worst sites.
In order to analyze this situation in detail, the surveyed stores were divided into quadrants labeled Q1, Q2, Q3, Q4 (Table 2).

Table 2. Values of CO_2e by quadrants [kg/100k visits].

Quadrant	Quantity	Average	Std. dev.
Q1	24	3.740	0.673
Q2	23	5.744	0.662
Q3	24	7.688	0.661
Q4	23	17.633	11.561

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In quadrants Q1, Q2 and Q3, the standard deviation of the results is practically the same, with a practically linearly increasing mean value of the index. The case is different in the Q4 quadrant, where the standard deviation is close to 2/3 of the mean, and in the box plot three observations are even outside the whiskers. This means that the collection of e-commerce sites in Q4, which includes the worst sites in terms of carbon footprint, is the most diverse.

3.3 Discussion

The results of the analysis show that the largest Polish online stores differ significantly in terms of their carbon footprint, with the CO_2e value of the worst being more than 16 times higher than that of the best. This indicates that there is great potential for reducing the negative environmental impact of e-commerce in Poland. It is worth noting that about 10% of the e-shops with the highest carbon value were responsible for such a wide spread of results. If these were omitted, the difference between the worst and best results would decrease by more than 3 times (from 1644% to 466%). This is still a large gap, however, and justifies the work to optimize websites through sustainability measures, such as reducing data transfer (e.g., by reducing the quality of image files), improving the user experience (e.g., by making it easier to search for products and content), using "green" data centers, and raising environmental awareness among customers.
However, the assumptions and simplifications made in the algorithm used must be kept in mind. While they are acceptable at a general level and provide a rough estimate of the carbon footprint of e-commerce websites, they should be improved for detailed analysis. The main changes to the CO_2e calculation algorithm described above should include:

1. the location of end customers, due to the varying values of CO_2 emissions per kWh produced in each country,
2. end-user devices due to differences in power consumption,
3. the ratio of returning customers to new customers - this metric should be related to the length of time content is cached on end user devices,
4. detailed information about the data center in use, including energy intensity and location,
5. dynamic adjustment of the values of the parameters used in the calculations to energy production market changes.

With this approach, it would be possible to dynamically incorporate changing values into the calculation of the carbon footprint of e-commerce.

4 Future research and conclusions

This paper underscores the importance of conducting regular carbon footprint assessments for e-commerce websites and encourages the adoption of sustainable

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practices to minimize the ecological consequences associated with online shopping. E-commerce sites generate carbon emissions throughout their lifecycle, from the manufacturing of electronic devices and infrastructure to the operation of data centers and the delivery of goods. It is important to note that the carbon footprint of each e-commerce platform varies based on factors such as energy sources, transportation methods, and overall sustainability practices. Efforts can also be made to optimize the amount of data sent during online shopping, thereby reducing environmental costs, and one direction is to modify and customize the user interface. However, it is important to keep in mind that reducing the carbon footprint of an online store's website may be associated with a decrease in its perceived usability (e.g., due to a decrease in images quality). Such a situation can be a business problem, especially if the e-shop's customers are not engaged in sustainability. If problems arise, it may be worth considering implementing a solution that uses multi-variant user interfaces [20] to allow customers to choose between visual attractiveness and reduced environmental impact.
The results of the study conducted and described in this paper show that there is a wide variation between the carbon footprints of online stores. This means that there is potential for action to optimize environmental impact. This is crucial given the growing importance of e-commerce in the economy and the increasing traffic to online stores. It is necessary to remember, but also to make customers aware, that every time they visit a store's website, refresh it, browse products, etc., there is a carbon footprint. The number of visits, often in the millions per day, multiplies these values every day. The research also included a verification of the data centers used. Some are actively working to reduce their environmental impact. Future work will include expanding the algorithms for calculating the carbon footprint of e-commerce to include as many influencing factors as possible. A reliable and accurate mechanism for analyzing the environmental impact of e-commerce stores can provide a tool for designers to optimize the user interface, but also point in other directions to minimize CO_2 emissions. Such a solution could also provide an incentive for e-commerce customers to engage and contribute to eco-friendly activities. Its practical implementation would be a step toward a more environmentally responsible e-commerce sector that aligns business practices with the global sustainability imperative.

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