WEBSITE GREENNESS USING A USER-CENTERED DESIGNED EXTENSION

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Abstract - The escalating energy consumption of data centers and the continuous growth of internet usage have brought the sustainability of websites into sharp focus. Carbon (CO_2) emissions from online activities constitute a significant, yet often overlooked, portion of total greenhouse gases compared to traditional sectors like transportation. Therefore, the concept of a green website, which refers to optimized infrastructure, has become essential. To directly measure the websites, a browser extension was designed and implemented to independently gauge the energy consumption and CO_2emission rates of web pages. The developed algorithm operates based on the total data size and the number of Hypertext Transfer Protocol (HTTP) requests, estimating each page's CO_2 footprint by calculating the energy consumed during the loading process.The extension analyzes key indicators of optimized infrastructure, including page weight, background color, image format and dimensions, hosting type, the number of redirects, and the use of external scripts. This tool accounts for data size analysis, as well as the optimization of JavaScript and other influential factors. The developed extension successfully provided accurate and scalable data without compromising user privacy. Data were collected and analyzed from tests on 49 diverse, highly-trafficked websites to provide a comprehensive picture of website performance and sustainability.Our findings reveal that actions like data compression, reduced number of requests, and image optimization can improve infrastructure efficiency and significantly lower CO_2 emission rate. The results clearly demonstrate that sustainable web design can not only mitigate environmental impacts but also enhance the quality of the user experience.

Keywords - Green websites, Browser extension, Carbon footprint, Energy consumption, Performance indicators, Web sustainability

I. INTRODUCTION

The web, or the World Wide Web (WWW), has today become the primary platform for information exchange, communication, and the provision of digital services across the globe. From news websites and online stores to social networks and government systems, all are part of this vast space that has transformed human daily life [1].This transformation has blurred the boundaries between physical and digital activities; for example, luxury brands have combined architectural expertise with the skills of virtual environment designers to create spaces that resonate deeply with their audiences and maintain a distinctive brand impact in both physical and digital environments[2].In the current digital age, network security and privacy have become two fundamental pillars for building user trust in the online space. Network security is a collection of technologies, policies, and measures implemented with the aim of protecting data and preventing unauthorized access [3]. Alongside this, the preservation of user privacy ensures that their personal information is not disclosed or exploited without consent [4].

Protecting personal data and reducing reliance on foreign services are crucial for both maintaining user security and promoting the digital independence of communities. [5] In addition to this principle, as web technologies expand, their environmental impacts have garnered increasing attention. The end user, as a consumer of digital services, plays a significant role in this area, benefiting from websites without being involved in their design or management. The choices of these users, such as using low-power browsers or interacting with optimized websites, help reduce their carbon (CO_2) footprint.Over the past several years (2010–2025), extensive research into climate change and energy consumption within the field of information technology has established the concept of "green websites" as an emerging area of applied research. Previous studies have provided theoretical frameworks and standards for reducing energy consumption and optimizing the web. For example, Wirtz (2019) [6], Müller [7], and Hasan et al. (2013) have all emphasized the necessity of sustainability in digital infrastructures. Additionally, the Software Carbon Intensity (SCI) indicator (Green Software Foundation, 2022) and the Findable, Accessible, Interoperable, and Reusable (FAIR) principles have provided tools for measuring and improving digital sustainability. Findings from Nature Communications (2024) [7] have revealed that digital content consumption generates 229 kg of CO_2 annually per person, which accounts for a significant portion of the allowableCO_2 budget to keep global warming below 1.5°C.These studies have highlighted the urgent need to design green websites and reduce CO_2 footprints. In this regard, web design and architecture have also received attention. Greenwood (2021) [8] and Frick

(2016) [9] have emphasized the importance of content optimization, reduced image sizes, and low-power coding to enhance web sustainability. The W3C has also provided a comprehensive framework for sustainable website design by publishing the Web Sustainability Guidelines (WSG) 1.0 (2023) guidelines. Recent analyses from arXiv (2024) [10] have pointed to lightweight, independent methods for estimating website energy consumption at the browser level, which have paved the way for the development of user-side analysis tools.

In contrast to prior research and studies in the field of sustainability assessment, websites have often relied on server-centered data or external Application Programming Interfaces (APIs), which has led to limitations, such as technical complexities and challenges related to user privacy. These studies have generally overlooked the capabilities of modern browsers for estimating energy consumption and have not considered user privacy as a key priority. However, challenges like the lack of unified criteria for sustainability assessment and the gap between theoretical frameworks and practical application have remained major obstacles. This is in contrast to earlier research, which primarily focused on server-centered optimization and paid less attention to the end-user experience and scalability for smaller websites.

The issue this paper addresses is how to use modern browser-based, client-side analysis tools to accurately assess the environmental sustainability of websites in a user-centered manner, while preserving user privacy and reducing reliance on external services. The study hypothesizes that by leveraging lightweight and independent browser-level technologies, an efficient and scalable method for estimating the CO_2 footprint of websites can be provided, which is not only highly accurate but also implementable for small and medium-sized websites by reducing technical complexities. This research aims to investigate whether this approach can bridge the gap between theoretical frameworks of web sustainability and their practical application, providing integrated indicators for evaluating the greenness of websites.

II. METHOD

An independentclient-side browser extensionwas developed instead of using common analytical services like Google Analytics. This extension used lightweight technologies and standard browser APIs, such as Performance API and Network API, to collect various data during page loading. Given the concept of the green web, which emphasizes optimized infrastructure to reduce energy consumption and achieve sustainability, and by examining previous studies, specific indicators were extracted to enable the measurement of green web practices.The extracted indicators included the size of various resources [images, JavaScript, Cascading Style Sheets (CSS), fonts, and videos], the number of requests [including third-party requests], key temporal indicators [including load time, First Contentful Paint (FCP), Largest Contentful Paint (LCP), and Time to Interactive/Interaction to Next Paint (TTI/INP)], as well as the CO_2 emission rate per page view. To evaluate these indicators, a unique algorithm was developed (Appendix 1) that analyzed each indicator and ultimately determined the greenness of each examined sample based on its score.

The CO_2 emission rate (CO_2 footprint) of the pages was calculated using a scientific algorithm based on the Green Web Foundation model and the latest version of the Sustainable Web Design Model (SEDM) v4 (2025)(Appendix 2). The algorithm first converted the total resource size of each page into gigabytes (GB). Then, the end-to-end energy consumption of the network and data centers was calculated with a coefficient of 0.193 kWh/GB.Next, the CO_2 emission rates were estimated based on the global CO_2emission intensity ($429gCO_2e/kWh$), and the output was rounded to two decimal figures. These calculations enabled an approximate comparison of the environmental impacts of different pages and an energy-centered performance analysis. The data wereprocessed on the users' browser-side and visualized in real time, making the analyses scalable, accurate, and based on preserving privacy. Exploratory Data Analysis (EDA) and multivariate analysis were used to examine the relationship between technical performance and environmental impacts of websites, and the results were presented using multi-part and doughnut graphs.

The data collection process took place on August 7, 2025, from 10:00 AM to 2:00 PM Tehran time. This time frame was selected to minimize fluctuations in internet traffic and significant changes in network speeds. For some websites filtered in Iran, it was necessary to use a Virtual Private Network (VPN), which increased page load times and altered time-based indicators, such as load time, FCP, and TTI. This factor was accounted for as an influential variable in the final data analysis.

The experiments were conducted in a controlled environment with minimal interference from other background programs on a Dell Latitude 7440 laptop. The device was connected to the internet via a wireless fidelity (Wi-Fi) network. The internet source was a Fourth Generation Long Term Evolution (4G LTE) Mobile Hotspot, and its speed was monitored during the experiments using the Speedtest.net tool. The speed ranged from 14.5 to 26 Mbps (with an average of approximately 20 Mbps). To minimize the effects of environmental noise and network

fluctuations, the testing location was chosen to have strong 4G signal coverage, and the device was positioned a short distance from the internet source. Additionally, energy-saving features and automatic operating system and browser updates were disabled during the experiments to ensure that the collected data were solely influenced by website loading. To analyze the data, 49 of the most visited websites were selected based on up-to-date and credible sources, including the Wikipedia page on the "list of most-visited websites."

These websites covered a diverse range of fields, including social networks, search engines, video platforms, and online stores, to allow for a comparison of environmental impacts across different user scenarios. The necessary data from these websites were extracted using a dedicated browser extension.

III. RESULTS

This article aimed to present a user-centered, browser-side analysis tool-based approach to evaluating the environmental sustainability of websites.This approach, without relying on external services and while preserving user privacy, accurately and scalably estimates websites' CO_2 footprints using lightweight, independent technologies, providing practical indicators for a "green web." The data obtained from browser-based, client-side analysis tools provided an accurate and user-centered picture of website performance and sustainability. As shown in Figure 1, these data included the size of various resources [images, JavaScript, CSS], the number of requests, load time, FCP, TTI, and CO_2 impact. This set of indicators allowed for the evaluation of both the technical performance and environmental sustainability of websites, and enabled an examination of the relationship between them.

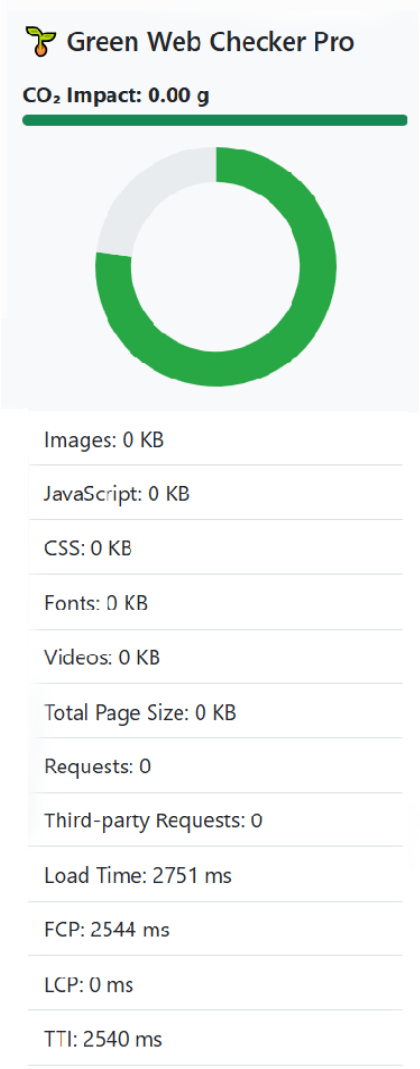


Figure 1. Green web pro extension: Performance overview of the designed extension applied to various websites

3.1 Analysis of Page Size and Resource

Consumption

Total page size was a significant indicator in determining bandwidth consumption, loading speed, and environmental impacts.The websites with the largest page sizes were vk.com (2439 KB) and www.roblox.com(2200 KB). In both instances, JavaScript page size was the primary contributing factor (2439 KB and 2200 KB). This is typically due to the extensive use of interactive modules and client-side scripts, significantly increasing the browser's processing load. Additionally, sharepoint.com fell into this category with 1397 KB of JavaScript, as did xhamster.com with a high combination of images (554 KB) and scripts (726 KB).The www.fandom.com (943 KB) was acompelling example where CSS files accounted for the largest portion of the total size (508 KB). This large size of CSSs could be attributed to heavy graphic design or the use of extensive CSS libraries. Another website, www.samsung.com (919 KB), had a balanced mix of images (117 KB), JavaScript (375 KB), and CSS (427 KB), indicating the simultaneous use of multiple highly-sizedresources.Websites like www.microsoft.com (7 KB), www.amazon.com (28 KB), and www.youtube.com (19 KB) were excellent examples of optimization, demonstrating that a positive user experience can be provided with very small file sizes. Other websites, such as www.facebook.com (9 KB) and www.msn.com (8 KB), also fall into this category due to their highly lightweight design.



Figure 2. This graph shows the evaluation of the total page size (KB) indicatoron the assessed websites

3.2 Analysis of Temporal Indicators

3.2.1 Total Load Time

The longest total load times were observed on www.tiktok.com(119,511 milliseconds [ms]) and www.temu.com(59,423 ms). Both websites exhibited slow performance due to a high number of requests and a large data size. The websites www.globo.com (41,254 ms) and duckduckgo.com (40,398 ms) were also among the slowest; in the case of globo.com, this issue was exacerbated by a heavy reliance on third-party resources. Conversely, the fastest load times belonged to web.telegram.org (766 ms) and www.xnxx.com(1,145 ms), which were likely due to effective caching, pre-loaded content, and a

lightweight architectural design.A long FCP time generally indicates a delay in rendering the main content. On this indicator, www.tiktok.com(57,454 ms) and duckduckgo.com (8,348 ms)exhibited the worst performance. The best FCP performance belonged to web.telegram.org (497 ms) and www.xnxx.com(605 ms).Websites like www.tiktok.com(60,891 ms) and www.temu.com(24,227 ms) had the highest TTI, meaning a significant delay in full interactivity. In contrast, web.telegram.org (269 ms) and www.xnxx.com (520 ms) delivered the best performance on this indicator.Figure 3 presents the temporal indicators based on the aforementioned classification applied to all specified websites, and the results are reported accordingly.

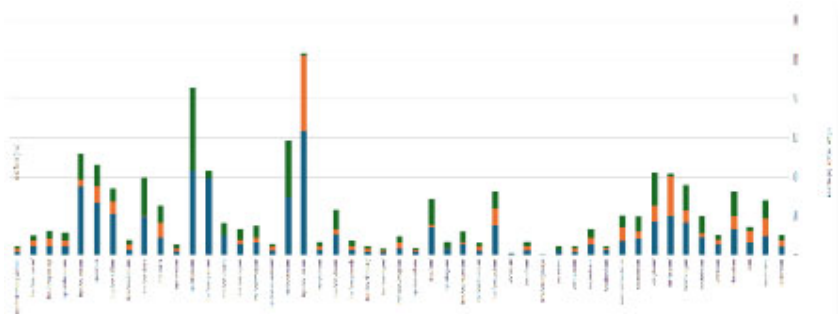


Figure 3. This graph illustrates the load time, First Contentful Paint (FCP), and Time to Interactive (TTI) parameters.

3.3 Analysis of Carbon Impact (CO2 Impact)

As shown in Figure 4, the highest CO_2 impact belonged to uk.pinterest.com, accounting for the largest share of total CO_2 emissions,whichwere primarily due to its largesize of JavaScript data and reliance on a significant number of third-party requests. Following this, the websites www.roblox.com, vk.com, and sharepoint.com had the next-highest CO_2 footprints, respectively. In contrast, the lowest CO_2 impact (zero or near-zero) was observed on websites, such as www.netflix.com, www.wikipedia.org, www.tiktok.com, and www.temu.com, which either had very low page sizes or utilized methods like data compression and comprehensive client-side caching.

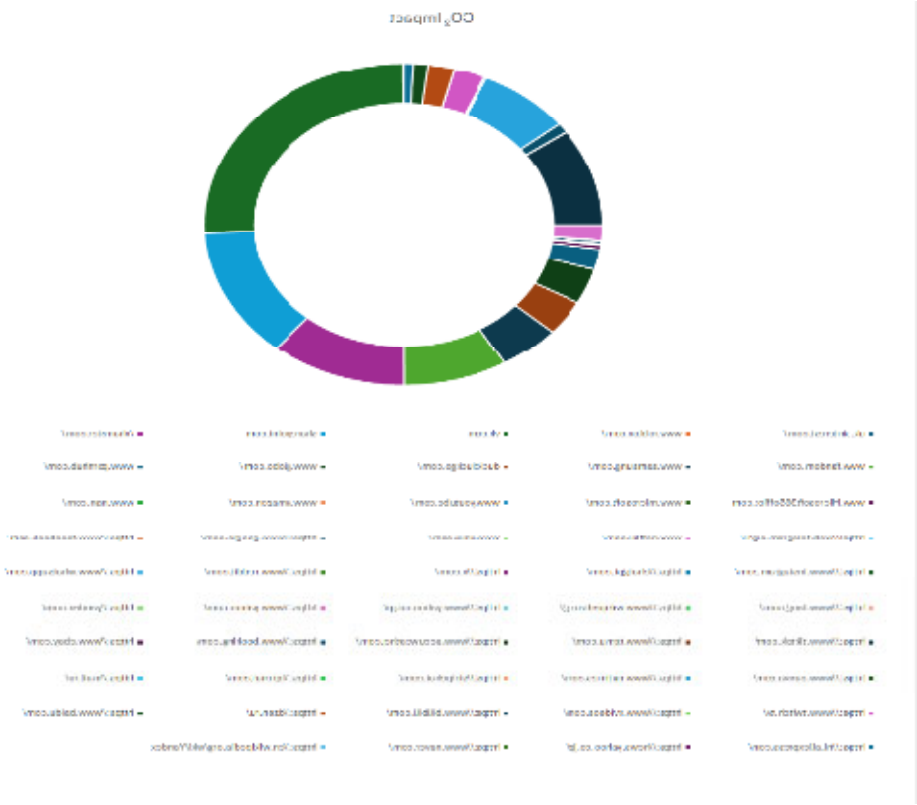


Figure 4. This graph illustrates the evaluation of the carbon impact indicator on websites.

3.4 Analysis of Third-Party Requests and Reliance onThird-Party Resources

An analysis of third-party requests and reliance on third-party resources(as shown in Figure 5) revealed that the highest number of requests belonged to www.tiktok.com(357 requests:173 first-party and 184 third-party requests). This was followed by www.globo.com(347 requests: 167 first-party and 180 third-party), and www.booking.com(250 requests: 120 first-party and 130 third-party). This high rate of requests resulted in delayed loading, higher energy consumption, and reduced security.In contrast, websites likewww.bing.com and web.telegram.org had the lowest number of requests, with 2 and 4 respectively, all of which were first-party, which contributed to better speed and efficiency. In terms of reliance on external resources, websites like www.bing.com and web.telegram.org were in the best position regarding security and privacy, with zero third-party requests. Conversely, uk.pinterest.com and www.globo.com were almost entirely dependent on external resources.

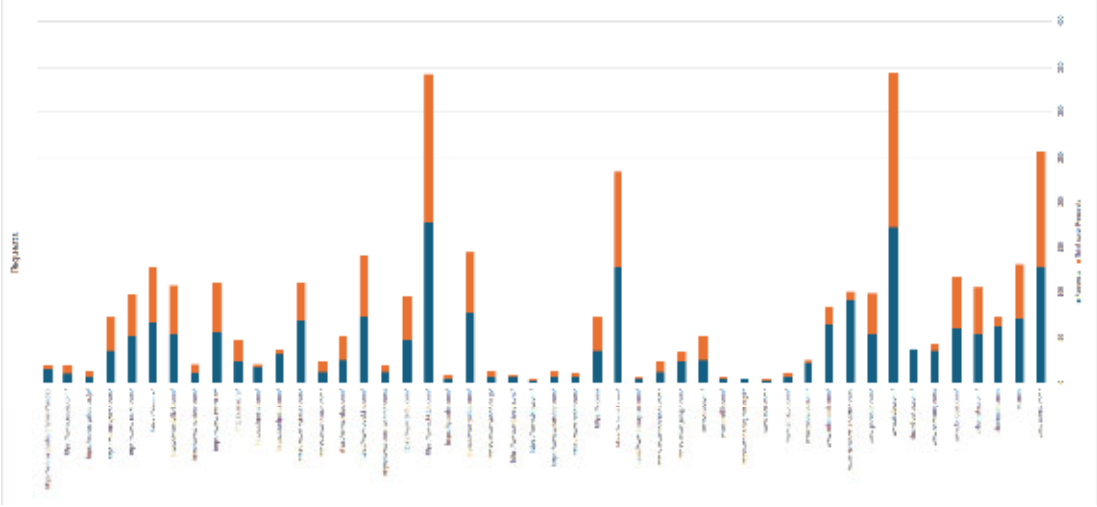


Figure 5.This graph compares the total number of requests and the number of third-party requests across different websites.

3.5 Analysis of JavaScript Files

The size of JavaScript was the most significant factor increasing page size and CO_2 impact. The high number of requests, especially third-party requests, directly caused slower load times and increased energy consumption. According to Figure 6, optimized and lightweight websites,such as microsoft.com and amazon.com demonstrated,showed that efficient design could lead to both a fast user experience and a low environmental impact. The strong differences in theseindicators reveal that a uniform standard for website sustainability has not yet been adopted.

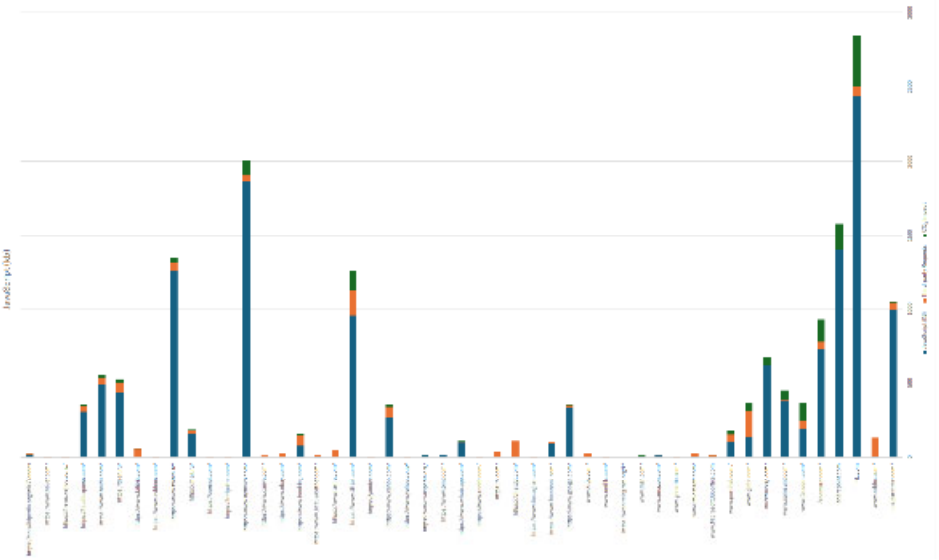


Figure 6. This graph compares the files of JavaScript (KB), third-party requests, and carbon impact for various websites.

IV. DISCUSSION AND CONCLUSION

In this study, modern browser-based, client-side analysis tools were used to examine the technical performance and environmental sustainability of 49 of the world's most-visited websites. The results revealed significant differences among these websites. For example, websites like vk.com and www.roblox.comgenerated long load times and substantial CO_2 emissions due to their large resource sizes (2,439 KB and 2,200 KB, respectively) and high numbers of requests. Conversely, optimized websites, such as www.microsoft.com (only 7 KB) and www.amazon.com (28 KB) achieved under one-second load times and near-zero CO_2 footprints.These findings confirm that reducing data size and optimizing resources can simultaneously improve user experience (by decreasing load times and enhancing interactivity) and environmental sustainability (by lowering energy consumption and greenhouse gas emissions). Such results are consistent with previous studies. For example, Greenwood (2021) [9] emphasized the importance of reducing the size of images and excessive JavaScript codes, while Frick (2016) [10] highlighted the direct impact of web design decisions on energy consumption.

A comparative analysis reveals that the present approach complements past research. Most previous studies, such as Andrae and Edler (2015) [12], have focused on infrastructure aspects and the optimization of servers and data centers. In contrast, the current research concentrates on the end-user experience and client-side analysis, aligning with frameworks developed by Hasan et al. (2013) [7, 13] and studies by Wirtz and Müller (2019) [14]. These studieshighlight sustainable web development through browser caching, data compression, and the green software lifecycle. Moreover, the adherence of some websites to the FAIR principles (Wilkinson et al., 2016) [14] demonstrates that data accessibility and reusability can be aligned with reduced energy consumption.

One of the key innovations of this research was the development of a dedicated browser extensionbuilt on the standard Performance API and Network API, whichcalculates performance and CO_2indicators without transmitting data to external servers. This lightweight and self-contained approach, unlike tools like Google Analytics, respects user privacy while providing accurate and scalable data. The results align with recent research from arXiv(2024) [11], recommending using browser-based estimation methods to calculate web energy consumption. Additionally, using the Sustainable Web Design Model (SEDM) v4(2025) and Green Web Foundation data with updated coefficients (0.193 kWh/GB and 429 gCO_2e/kWh) improved the accuracy of CO_2 emissions estimation. This model is consistent with new standards like the WSG 1.0 (W3C, 2023) and the SCIindicator from the Green Software Foundation (2022) [15], which have also been formalized in the new ISO/IEC 21031:2024 standard.

From a scientific standpoint, the present research, consistent with data from the Web Almanac (2024) [17] and modern tools like SiteBeaconCO2.js, demonstrates that “page weight” is a key indicator for estimating energy consumption and CO_2 footprint. The global average web page size (7-8 MB) is still far from the recommended level of under 1 MB. Furthermore, the use of responsive techniques and lazy loading directly impact reduced data transfer and energy consumption. The heavy reliance on third-party resources—such as the 184 external requests on www.tiktok.com—increased load time, energy consumption, and privacy risks. This finding aligns with the warnings of Zuboff (2019) [4] regarding surveillance capitalism and Mozilla (2023) [18] concerning the hidden costs of internet usage. In contrast, websites like www.bing.com, with only two first-party requests, showed that reducing reliance on external resources can strengthen environmental sustainability in addition to improving security and speed.

This research had several significant strengths: The development of a lightweight, independent tool that did not impose additional system load; the simultaneous measurement of technical, temporal, and CO_2indicators; and the analysis of a diverse sample of 49 websites from various domains. Additionally, the CO_2 calculations were aligned with the principles of the SCI and WSG 1.0, which enhanced the scientific validity of the results. However, the study also had limitations: The restricted scope of the sample (49 websites), a short experimental duration (four hours on August 7, 2025), the influence of network conditions (4G LTE and VPN), and the use of only one device (Dell Latitude 7440). Furthermore, the CO_2 calculations were based on global parameters and did not account for regional differences in electricity CO_2 intensity. These limitations are similar to those reported in Nature Communications (2024) [13]. Lastly, the research focused solely on initial page loading, and post-loading interactions (such as scrolling or dynamic loading) were not examined.

Therefore, as shown by the results of this research, client-side analysis using lightweight, independent tools can provide accurate performance and CO_2 data, preserve user privacy, and align improved user experience with a reduced environmental footprint. By bridging the gap between theoretical frameworks and practical applications in the field of green web, the findings pave the way for the development of faster, more secure, and more sustainable websites. It is hoped that these results will inspire policymakers,

designers, and researchers to prioritize digital sustainability in the future.For future research, it is suggested to expand the scope of the analysis: Increasing the number of websites to over 200 samples across diverse languages and domains; conducting tests on various networks (fiber optic, 5G) and in different geographical regions; integrating real hardware energy consumption data (e.g., device power measurements) to improve accuracy; and combining client-side analysis with server-side data for a more comprehensive picture of web sustainability. Additionally, investigating the impact of complex content (videos, animations) and long-term user behavior on the CO_2 footprint is essential. The use of new reports, such as the Environmental and Energy Study Institute (EESI) (2025) [19] report, which warns of an increase in the share of global electricity consumption by data centers (up to 8% by 2030), can help guide research priorities

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