Carbon Footprint Analysis of Web Page Development

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Abstract- *This study presents a novel approach to calculate the carbon footprint of WebPages, which is a critical step towards understanding and mitigating the environmental impact of internet usage. The carbon footprint of webpages is calculated by considering various factors such as the energy consumption of servers, data transmission, and user devices. A detailed methodology is proposed, which includes the estimation of energy consumption based on webpage characteristics and user interactions. The results show that different webpage elements contribute differently to the overall carbon footprint, highlighting the importance of optimizing webpage design and content delivery for sustainability. This study also discusses the implications of the findings for web developers, businesses, and policymakers, emphasizing the need for sustainable practices in website development and maintenance.*

Keywords- Carbon footprint, Webpages, Internet usage, Energy consumption, Web development, Environmental impact, Data transmission,

I. INTRODUCTION

The internet has seamlessly integrated into modern life, serving as a vital tool for work, leisure, and connectivity. However, this reliance on digital connectivity comes with a significant environmental cost, contributing to our carbon footprint[1] The electricity that powers the internet is often derived from carbon-emitting sources, such as coal-fired power plants. Moreover, the data transmission and processing involved in browsing the web also result in carbon emissions[2]

To mitigate the environmental impact of internet use, particularly web browsing, understanding and measuring our digital carbon footprint is essential[3] This is where a carbon footprint calculator tailored for web pages can play a crucial role. By analyzing factors such as server location, page views (new and returning), and content types (e.g., plaintext, images, videos), this tool can provide valuable insights into a web page's carbon footprint[4]

The calculator goes beyond mere assessment, offering actionable recommendations to optimize a web page's energy consumption These recommendations can help tech makers and web developers make informed decisions to reduce the carbon emissions associated with their digital content[5]

While similar tools exist, many fall short by not providing specific, actionable recommendations for reducing a web page's carbon footprint. This calculator aims to bridge that gap by offering practical solutions to minimize the environmental impact of web pages[6]

Moreover, the project is open source, with its source code available on GitHub. This transparency allows for collaboration and further improvements, ultimately contributing to a more sustainable digital landscape[7]

In summary, the development and implementation of a carbon footprint calculator for web pages mark a significant step toward reducing the environmental impact of our digital activities. By leveraging this tool and its recommendations, we can take meaningful action to lessen our carbon footprint in the digital realm[8]

II. LITERATURE REVIEW

The literature on carbon footprint analysis of web page development highlights the importance of considering environmental impact in website design. Studies suggest that optimizing code, using efficient hosting services, and minimizing data transfers can significantly reduce the carbon footprint of web pages, contributing to sustainability efforts.

Karen Valls-Val et.al (2021) This study reviews carbon footprint assessment in Higher Education Institutions (HEI), analyzing methodologies, tools, and results. Findings show a wide range of emissions and a need for standardization in metrics, data collection, and emission factors to improve sustainability practices in HEI[7]**Jianping Wanget.al (2014)**This paper explores research methods for studying various carbon footprints and compares carbon footprint assessment standards. It analyzes goals, principles, and methods for assessing organization and product footprints, highlighting the need for improvement in existing standards[4]**PN Robinson et.al (2023)**Sustainability in healthcare is gaining recognition, with a focus on reducing carbon footprints of surgical operations. A systematic review found that medical devices and consumables are major emission contributors, highlighting the need for standardized research to guide sustainability efforts[6]**RRK Sharmaet.al (2020)** This study reviews the relationship between carbon footprint (CFP) and sustainable supply chains, emphasizing the need for greener manufacturing practices. It finds a focus on environmental impacts and suggests integrating CFP management into supply chain strategies for sustainability[3] **Yongfeng Ma et.al (2023)** This article reviews current methodologies for calculating CO2 emissions from transportation, highlighting discrepancies and emphasizing the need for reliable methods to reduce emissions and raise environmental awareness[2]**Amy Booth et.al (2020)** Healthcare's impact on climate change underscores the importance of quantifying its carbon footprint. Current efforts are hindered by data limitations and methodological challenges, particularly in developing nations. Improved data availability and methodology are crucial for global climate action[5]**Miranda-Morenoet.al (2020)**The authors reviewed sustainability accounting/reporting focusing on climate change (SDG 13). They found a lack of literature on managing climate change aspects, suggesting future research areas for accounting scholars to integrate climate change mitigation into their work[8]**N. Lovehagen et.al (2023)** This study examines the embodied carbon emissions of user devices in accessing networks, revealing that the second approach, despite allocation sensitivity, provides the most reasonable estimate of about 180 million tonnes CO2e in 2020. Representative emissions for user devices are also derived[1]

III. METHODOLOGY

The methodology for the carbon footprint analysis of web page development involves assessing the environmental impact of various stages, including design, coding, and hosting. It includes calculating energy consumption, emissions, and waste generation to quantify the carbon footprint.

Transfer of Data and Energy Consumption of the Server

When a web page is accessed, the hosting server consumes energy to process the requested data. This includes retrieving the data from storage, processing it, and sending it back to the user's browser. To calculate the carbon emissions per kilobyte (KB), the average energy required to transmit 1 KB of data from the server to the client is considered, along with the average carbon emissions per kilowatt-hour (kWh) of electricity in the United States, where the data is primarily sourced from. This data is constantly updated using a data crawler to ensure the calculator reflects the most recent figures.

The distance the data travels also impacts the energy consumption. For example, if the server is in the United States and the user is in Europe, more energy is needed for the data transmission. To account for this, web pages not using a Content Delivery Network (CDN) are penalized by a factor of 0.2. CDNs distribute data through a network of servers globally, reducing the distance data needs to travel. Most web hosting providers offer CDN services, such as Cloud flare.

The location of the web server also plays a role, as countries generate electricity with varying carbon intensities. For instance, coal-powered plants emit more carbon than nuclear-powered ones. The calculator adjusts the carbon intensity based on the 2021 data for each country, penalizing or rewarding the web page accordingly based on the United States' carbon intensity.

The energy consumption of the web server depends on the number and type of page views. For example, initial page views require downloading all resources, while returning views download fewer files due to browser caching. Modern browsers like Google Chrome and Firefox cache static files, reducing the need for repeated downloads. Web server software, such as NGINX, can also dictate caching policies to optimize resource delivery and reduce energy consumption.

Client Device Consumption of Energy

The methodology for assessing the carbon footprint of web pages involves considering both server-side and client-side energy use. Server-side energy use refers to the energy consumed by the servers hosting the website, while client-side energy use is the energy used by the user's device to process and display the downloaded data.

For this study, we focus on smartphone users, assuming an equal distribution between WiFi and cellular data usage. Research indicates that smartphones consume approximately 98.1 mW of energy per minute during web browsing. Given that energy consumption is highest during page load, we use an average time on page of one minute.

To calculate CO2 emissions, we consider the changing emissions per kWh of electricity in the US. The client-side energy use depends on the web page's content, with pages containing more images requiring more processing energy. To account for this, we use the Largest Concertful Paint (LCP) metric, which measures the time taken for a web page to fully render, including image loading and JavaScript operations.

According to Google Lighthouse, the average LCP metric is 2.5 seconds. We penalize or reward web pages based on whether their LCP is above or below this average. This approach allows us to estimate the energy consumption and CO2 emissions associated with different types of web pages, providing insights into how website design impacts environmental sustainability.

IV. RESULT AND DISCUSSION

To assist technology developers in minimizing the carbon footprint of the webpage, the calculator provides practical suggestions. The recommendations put forth are founded upon the performance audit guidelines and tools provided by Page Speed Insights. I selected assessments of performance that are pertinent to the carbon emission impact based on their recommendations.

Table 1. Audits and metrics used for recommendations

Audit / Metric	**Carbon Impact**
Total Blocking Time (TBT)	High Total Blocking Time means the client device CPU is extensively used during page load. Optimizing this value lowers the energy usage / CO2 emission of the client device.
Main-thread work	Delivering smaller JavaScript payloads at the appropriate time will decrease the useless JavaScript parsing and decrease energy consumption / CO2 emission.
First CPU Idle Time	Lowering the time and workload of the CPU will decrease energy consumption / CO2 emission for client devices.
Efficient static asset cache policy	Long caching policies for static files [5] decreases returning pageview transfer sizes and lowers carbon emission of servers transferring files to client devices.
JavaScript execution time	Delivering smaller JavaScript payloads at the appropriate time will decrease the useless JavaScript parsing and decrease energy consumption / CO2 emission.
Largest Concertful Paint (LCP)	High LCP might mean your web page is intensive in terms of images or styling. Decreasing this time metric lowers the energy usage / CO2 emission of client devices.
Speed Index (SI)	Decreasing SI lowers the energy usage / CO2 emission of client devices.
Cumulative Lay out Shift (CLS)	When the CLS metric is high, the graphics processor of the client device uses additional energy, optimizing this index can lower energy usage / CO2 emission.
Initial server response time	High response time might mean either the server is far from the client and without a CDN service, or there are intensive backend tasks, optimizing this value will decrease carbon emission of servers transferring files to client devices.
Audit / Metric	**Carbon Impact**
Lazy image loading	Lazy loading images helps lower data transfer and lowers carbon emission of servers transferring files to client devices. Additional not rendering off screen images helps decrease energy consumption by client devices.
Unmagnified CSS and JavaScript	Minifying CSS and JavaScript lowers data transfer and lowers carbon emission of servers transferring files to client devices.
Unused CSS and JavaScript	Tree-shaking unused CSS and JavaScript rules before deployment lowers data transfer and lowers carbon emission of servers transferring files to client devices.
Optimized images	Optimizing images lowers data transfer and lowers carbon emission of servers transferring files to client devices.
Text compression	Text compression lowers data transfer and lowers carbon emission of servers transferring files to client devices.
Responsive images	Using responsive images can lower data transfer for different device screen resolutions.
Legacy code serving	Not delivering legacy code for modern browsers will cause carbon emission of servers transferring files to client devices.
DOM size	Lower DOM size means lower data transfer and lower energy used / CO2 emitted during page rendering on client devices.
No document. Write	Page load time is affected by this audit, optimizing this index can lower energy usage / CO2 emission.

To optimize web page carbon emissions, the calculator provides actionable recommendations for tech makers based on Page Speed Insights performance auditing guidelines. Relevant performance audits are selected for their impa on carbon emissions. The web page is tested against metrics and audits in Table 1, and a report is generated and displayed on the results screen. Metrics are ranked as “Poor,” “Needs work,” or “Perfect” based on guideline scoring. Metrics ranked as “Poor” or “Needs work” offer links and guides for improvement. The results page of the calculator displays all metrics and their carbon impact explanations.

Software Architecture

This section will present a physical view, a use case view, and a process view of the software architecture for the carbon footprint converter project.

Use Case View

The following use case diagram illustrates the sequence of events that transpire when a user engages with the calculator utility application

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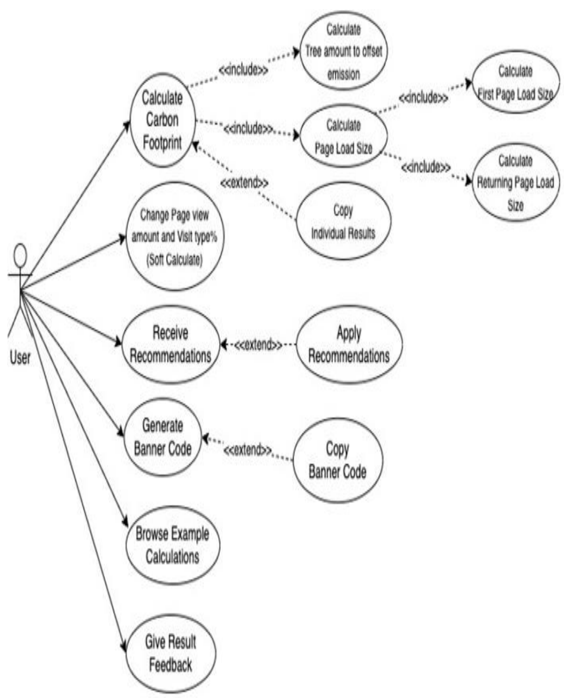

Figure 1. Use Case Diagram

As illustrated in Figure 1, the calculator utility was designed to be an integral component of the user's ongoing workflow. By calculating the desired web page, receiving recommendations, implementing those recommendations on their staging web page, and subsequently retesting it in a circular fashion, the user can observe the carbon footprint reduction of their web page. This is designed to be a continuous procedure, assisting the user in progressively reducing the ecological footprint of their website.

Physical View and Deployment

In order to render the results of a web page in its backend, the calculator downloaded the page and utilized a headless browser simulation to conduct resource-intensive audits on the data. Conquering every task within a time frame that satisfied the requirements of the users posed a challenge throughout the execution phase of this project. Parallel containerization of math and auditing duties resolved this issue. The calculation and processing of recommendations requires an average of twenty seconds to complete. Although a minute may be required to load a lengthy website. Due to the calculator utility performing a large number of computations in parallel over a brief period of time, the concurrent utilization of a significant amount of server memory and CPU power by the calculations may pose a deployment challenge. Utilizing a physical server that has restricted resources would impose a restriction on the number of concurrent users. This means that while twenty users concurrently utilize this utility for calculations, the twenty-first user must wait in queue for vacant server estate. Self-contained portions of the calculation are deployed as Function Containers (high-availability computation infrastructure that typically performs a specific underlying task and can be scaled horizontally) on the AWS Lambda in order to resolve this issue.

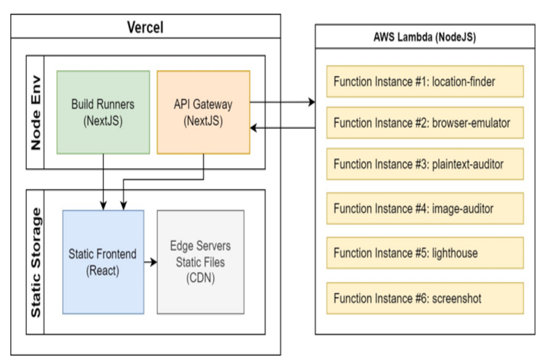

Figure 2. Deployment diagram for the calculator (arrows indicate information flow)

As illustrated in Figure 2, six distinct calculation functions are implemented as Function Instances, enabling them to execute concurrently when invoked. NextJS orchestrates the API gateway layer, which concurrently awaits and executes outputs from all function instances throughout a calculation. Subsequently, the gateway layer parses and transmits data via the frontend with JSON format. The precise responsibilities of each function instance are outlined in Table 2.

Table 2. Function Instances and their tasks

Function Instance	Function definition and task
location-finder	Determines the server country, determines CDN usage and calculates carbon intensity multiplier.
browser-emulator	Runs a headless browser emulator in order to calculate the time related metrics such as LCP, JavaScript execution time and SI (see Table 1).
plaintext-auditor	Audits and generates plaintext related recommendations such as Text Compression and DOM size.
image-auditor	Audits and generates recommendations for images, such as “Optimized Images” and “Responsive Images” (see Table 1).
lighthouse	Runs additional “Page Speed Insights” audits listed in Table 1.
screenshot	Takes a screenshot of the Largest Concertful Paint (LCP) with a headless browser emulator.

Technologies and Tools

Advanced engineering technologies for sustainable development encompass a wide array of innovative tools and methodologies aimed at reducing environmental impact and promoting sustainable practices. Green chemistry, a key component of this field, focuses on the design of chemical products and processes that minimize the use and generation of hazardous substances. Geo-environmental technologies play a crucial role in assessing and managing environmental risks, such as soil and water contamination, to protect human health and ecosystems.

Biotechnology is another pivotal area, where it offers sustainable solutions for various environmental challenges, including waste treatment, pollution control, and resource conservation. Catalysis applications in pollution control represent a promising approach to mitigating air and water pollution by promoting efficient chemical reactions that convert harmful pollutants into less harmful or inert substances.

Additionally, forensic science plays a significant role in environmental protection and sustainability by providing scientific evidence and analysis in legal proceedings related to environmental crimes. Overall, these technologies and tools collectively contribute to advancing sustainable development goals by addressing environmental challenges through innovative engineering solutions and scientific advancements.

V. CONCLUSION

The web application hosting the calculator is presently live and operational, inviting users to participate in open beta testing. Upon accessing the results screen, users are encouraged to evaluate the outcomes. A link to the GitHub issues page of the project is provided, enabling users to submit feedback, evaluations, and concerns regarding specific results.Through its comprehensive approach, the tool fills critical voids in existing solutions, enhancing accessibility and efficacy in carbon footprint reduction efforts for web pages. The provision of real-time guidance sets it apart, empowering users to make informed decisions and actively contribute to environmental sustainability within the digital sphere.Moreover, the open beta phase serves as a valuable opportunity for refining the tool's functionality and addressing user feedback. By fostering collaboration and engagement, the project aims to iterate and improve continuously, ensuring its relevance and effectiveness in mitigating the environmental impact of web page development.Overall, the introduction of this innovative tool marks a significant advancement in the realm of carbon footprint reduction for web pages. Its accessibility, functionality, and commitment to ongoing improvement reflect a concerted effort to address the environmental challenges associated with digital infrastructure, paving the way for more sustainable practices within the online ecosystem.

Future Scope of the Study

The future scope of the study "Calculate the Carbon Footprint by Using Webpages" encompasses several key areas for further exploration and development. Firstly, advancements in web technologies and data collection methods could lead to more accurate and detailed carbon footprint calculations. This includes the integration of real-time data on website energy consumption and server efficiency, as well as the development of standardized methodologies for carbon footprint calculation specific to webpages.

Secondly, there is a growing need for tools and frameworks that can help website developers and managers optimize their webpages for lower carbon emissions. This could involve the development of best practices, guidelines, and automated tools that can analyze webpage elements and suggest ways to reduce their carbon footprint without compromising user experience or functionality.

Additionally, the study could explore the potential for incentivizing or rewarding websites that have lower carbon footprints, such as through carbon offsetting schemes or certification programs. This could create a market-driven approach to reducing carbon emissions from webpages and encourage more sustainable practices in website development and management. Overall, the future scope of the study includes further research and development in the areas of data collection, methodology, optimization tools, and incentives, with the ultimate goal of reducing the carbon footprint of webpages and promoting sustainability in the digital domain.

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