

Beyond the map: A sustainability and carbon footprint audit of public geoportals

Karol Król  0000-0003-0534-8471

Department of Land Management and Landscape Architecture, University of Agriculture in Krakow

✉ Corresponding author: k.krol@urk.edu.pl

Summary

As the digitisation of public administration continues, the analysis of the environmental impact of platforms providing spatial data is becoming increasingly important. Public geoportals, while serving a crucial role in information dissemination and decision support, are rarely evaluated in terms of their CO₂ emissions or their compliance with environmentally sustainable design principles. In this study, ten selected public geoportals were examined using a comprehensive set of auditing tools, including Ecograder, Website Carbon Calculator, Digital Beacon, Kastor Green, Lighthouse, RankMatch, and the Green Web Evaluator AI agent. The evaluation focused on multiple dimensions, such as page performance, hosting solutions, resource size, accessibility, and the degree of SEO optimisation. The results revealed substantial variation in carbon emissions, ranging from 0.17 to 2.95 g CO₂ per page load, and highlighted numerous shortcomings in technical optimisation and compliance with WCAG accessibility standards. A strong correlation was observed between page size (MB) and carbon emissions, as well as a negative impact of redirect mechanisms on both performance and carbon footprint. These findings indicate the lack of a standardised model for building geoportals that balance functionality with environmental efficiency. The study concludes with a set of actionable recommendations aimed at supporting public institutions in developing geoportals that are more energy-efficient, accessible, and environmentally sustainable.

Keywords

quality audit • website quality • website sustainability audit • sustainable web design • digital decarbonisation • Green SEO

1. Introduction

The growing availability of spatial data shared through online map services, known as geoportals, has changed how citizens, public administration, and specialists make use of information [Król et al. 2024]. These services, often provided by public institutions, offer interactive maps, cadastral data, satellite images, and spatial analysis tools [Król and Szomorova 2015, Cegielska et al. 2018, Król 2024]. Although their informational and functional value is commonly known, the impact of geoportals on the environment remains poorly understood. In the context of rising environmental awareness and technological development, this represents a significant research gap.

Despite global efforts to reduce the carbon footprint of digital products, research so far has focused mainly on e-commerce, information, and corporate portals, overlooking public geoportals, which are particularly energy-intensive [Merbecks 2024]. In their case, high energy consumption is mainly caused by the handling of large geodata sets, including raster data and dynamically generated content, which directly translates into increased CO₂ emissions [Król and Sroka 2023]. The evaluation of such services requires an analysis of aspects such as the degree of resource optimisation, the use of environmentally friendly hosting, performance, compliance with the Web Content Accessibility Guidelines (WCAG) and Search Engine Optimization (SEO) principles. Geoportals exhibit a specific architecture involving high server load and frequent client-side content rendering [Król 2025a].

The aim of the research is to determine the impact of selected public geoportals on the environment and the extent of their compliance with the principles of sustainable website design. The study uses a structured comparative method, which allows not only to qualify the current technical state of the analysed websites, but also to formulate recommendations supporting the ecological transformation of digital public services. The analysis covered energy efficiency, compliance with SEO practices and the use of technologies reducing CO₂ emissions. Thanks to a unified scoring system, developed using selected audit tools, the study has a benchmarking character and results in practical guidelines for designing more environmentally friendly and accessible geoportals. The following research questions were addressed in the study:

- RQ1: How do the system architecture and data structure of public geoportals affect their carbon footprint?

Question RQ1 focuses on the technological drivers of CO₂ emissions, and thus it concerns technical features of geoportals, such as the number of components, map rendering methods, or the use of raster data, and how these translate into energy consumption and CO₂ emissions.

- RQ2: What technological and organisational barriers restrict the implementation of sustainable design principles in geoportals?

Question RQ2 shifts the research focus from assessing the technical parameters to identifying the causes, which allows for an analysis of the reasons why environmental optimisation practices for geoportals are not widely adopted.

The rest of the paper has the following structure: section two presents the theoretical background and a review of the literature on the impact of information and communication technologies (ICT) on the environment, with a particular focus on sustainable digital development and Green SEO auditing. Section three describes the research materials and methods, including the characteristics of the analysed geoportals and the specifications of the Green Web Evaluator AI tool. The fourth section presents the research results along with an interpretation of CO₂ emission indicators, accessibility, resource optimisation and a comparative analysis. The fifth section discusses the results in the context of the literature on the subject, pointing to new conclusions and possible directions for optimisation measures. The paper is concluded with a summary setting out the conclusions, practical implications and limitations of the study.

2. Background

As public services become increasingly digitized, there is growing interest in the impact of ICT on the environment. It is estimated that the ICT sector already accounts for 2–4% of global greenhouse gas emissions, and its share in the carbon footprint will steadily increase in the coming years [Freitag et al. 2021]. The sources of CO₂ emissions include not only data centers and servers, but also network infrastructure and end-user devices, including computers, smartphones, and the Internet of Things (IoT). Thus, the problem of ICT's impact on the environment has a systemic nature and requires comprehensive analyses covering various levels of digital infrastructure.

There has been a growing number of studies focusing on the so-called digital carbon footprint, i.e., emissions related to the operation of websites and web applications. For example, Sala et al. [2024] presented the Green Web Meter tool for assessing the digital ESG (Environmental, Social, Governance) performance of websites in real time. By integrating eight key KPIs (including energy efficiency, carbon footprint, accessibility, security, and SEO), the tool not only measures the environmental impact of websites, but also supports institutions and organizations in the practical implementation of strategies to reduce CO₂ emissions and enhance the quality of digital services. Król [2025b] developed the concept of a Green SEO audit, combining SEO website optimisation issues with an analysis of their environmental impact. This approach emphasises the need to view website performance and search engine rankings through the lens of digital sustainability, rather than focusing solely on technical and marketing considerations. Green SEO includes auditing energy efficiency, resource size and optimisation, hosting quality, digital accessibility (WCAG), and compliance with SEO best practices. This method not only improves the website's position in search engines, but also reduces their carbon footprint. In this way, the study by Król [2025b] fits into the trend of research on digital sustainability, indicating that environmental optimisation and online visibility can be treated as complementary rather than separate goals. Other studies have shown that invisible components of websites, such as programming libraries, external scripts, user activity tracking scripts, and large/high-volume graphics, can significantly increase energy consumption and, consequently, CO₂ emissions

[Pachilakis et al. 2023]. These results confirm that sustainable web design should also take into account hidden layers of code and resources that generate additional energy consumption.

The concept of digital sustainability assumes minimising the negative impact of digital technologies on the environment while maintaining their functionality [Riabova 2025]. However, previous studies have focused mainly on media and e-commerce, while public geoportals remain poorly represented in the literature. Yet, due to large volumes of raster data, interactive map modules and a high level of dynamics, map services can generate relatively high energy loads. At the same time, there is a lack of systematic audits of their accessibility, performance and environmental impact. As pointed out by Istrate et al. [2024], digital consumption and presentation of content, including geospatial data, should be designed with its potential environmental impact in mind. This points to the need to extend research on digital sustainability to include map services, which, by their very nature, can generate a significant carbon footprint.

2.1. Green SEO audit

Green SEO audit is a process of analysing the functionality and degree of optimisation of websites in terms of SEO and their impact on the environment. Its purpose is to identify areas for improvement and suggest optimisation measures that will make the website more energy-efficient, environmentally friendly, functional and user-friendly, while maintaining its visibility in search engines [Król 2025b]. Green SEO focuses on optimising content, code and data transfer to reduce energy consumption and CO₂ emissions [Confetto and Covucci 2021]. A Green SEO audit also includes aspects related to access to hosting services that use renewable energy sources or neutralise CO₂ emissions [Green Web Foundation 2025]. As a result, a Green SEO audit is a process that combines the analysis of traditional SEO factors with an assessment of the environmental aspects of website operation.

The procedure for auditing websites for environmental impact runs in several stages (Table 1). The first is a preliminary assessment, which includes identifying the sources of hosting power, analysing data transfer volumes and the number of HTTP requests generated by the website. The next step involves analysing resources, including measuring the size of graphic and 'system' files, e.g. CSS sheets, JavaScript code, assessing the used minification and compression methods, and configuring the cache and content delivery network (CDN). The third stage concerns environmentally friendly optimisation in the area of SEO, which is intended to improve the structure of content, links and metadata, and thus reduce the page loading time and related CO₂ emissions. In a further step, the website's compliance with selected standards and regulations is verified, such as: Web Sustainability Guidelines (WSG), Eco-Management and Audit Scheme (EMAS), ISO 14001, W3C, WCAG and ESG. This helps assess the degree of implementation of sustainable development and environmental responsibility principles at the organisational level. In this context, ESG is

understood as a set of assessment criteria covering environmental, social and corporate aspects. The final stage of the audit involves preparing a post-audit report with a summary of the results compared to the reference values and recommendations, including both quick wins and long-term optimisation strategies, along with the possibility of obtaining environmental certification (e.g. EMAS). The entire process emphasises the aim of achieving a real reduction in the carbon footprint of digital services [Rathor et al. 2023].

Table 1. Stages of a Green SEO audit

Stage of audit	Description of the stage
Initial assessment	Checking the hosting source (Greencheck API), website resource size, data transfer, and number of HTTP requests
Component analysis	Measurement of page size (MB; WebP/SVG, CSS, JS), compression, caching, and CDN usage
Green SEO audit	Audit of content, meta information, links, SEO
Certificates and guidelines	Assessment of compliance with WSG 1.0 (Web Sustainability Guidelines from W3C), EMAS standards, ISO 14001, GDPR and ESG principles
Report and recommendations	Summary of indicators, comparative analysis, identification of so-called 'quick wins' and long-term optimisation measures

The term 'quick wins' refers to optimisation measures that can be implemented relatively quickly, at low cost and without the need for a thorough website redesign. At the same time these measures can bring noticeable results, such as improved website performance, reduced CO₂ emissions or better SEO results. In the context of a Green SEO audit, quick wins are usually simple technical modifications that can improve the environmental and quality indicators of a website. Examples of such measures include implementing server compression (e.g. GZIP), converting images to more efficient formats (e.g. WebP), organising the hierarchy of HTML headers, introducing alternative texts for graphic elements and activating caching. These types of improvements can be introduced by small technical teams, and often they do not require fundamental changes to the website's architecture. Their importance stems from the fact that they provide initial confirmation of the effectiveness of the adopted optimisation strategy and can serve as a starting point for more advanced measures in the field of digital sustainability.

The W3C Sustainable Web Design Community Group plays a key role in the development of Green SEO. It is responsible for creating Web Sustainability Guidelines (WSG) 1.0, i.e. a set of 93 guidelines and 232 success criteria for assessing the environmental performance of websites [Wimalasena and Arambepola 2025]. They align web development with global ESG goals, facilitate the implementation of green hosting, data transfer optimisation and resource management. The Green Web Foundation also

provides tools for monitoring websites for CO₂ emissions. In addition, Green SEO also uses ISO 14001 and EMAS, i.e. environmental management standards for institutions, including public digital platforms [Pachilakis et al. 2023].

Geoportals hosting large amounts of spatial data generate significant data transfer and energy loads [Król and Sroka 2023]. Without proper optimisation, such services can emit significantly more CO₂ than typical information websites. Corrective measures based on Green SEO, including resource compression, caching and the use of appropriate hosting, can significantly reduce the carbon footprint of geoportals, shorten their loading times and improve UX. Furthermore, the application of WSG, ISO and EMAS standards not only supports digital sustainability goals, but also enhances the transparency and image of public institutions. Thus, geoportals can become an example of public digital services that are both functional and environmentally friendly [Rathor et al. 2023].

Considering the characteristics of Green SEO audits and the role of geoportals in the digital services ecosystem, it is justified to conduct empirical research based on uniform environmental and technological criteria. To ensure the comparability of results, websites representing various administrative levels and different technological solutions were analysed. The following sections of the study contain a detailed description of the data, evaluation methods and research tools, including the Green Web Evaluator AI module, which supports expert analysis of websites in the context of sustainable digital development.

3. Materials and methods

The study was designed on the basis of an approach combining quantitative and qualitative analysis, using standardised criteria for assessing the environmental and technical performance of geoportals. The methodology adopted allows for an objective comparison of websites representing different administrative levels, as well as diverse technological solutions. The analysis took into account both aspects related to hosting and the technical structure of the websites, as well as factors affecting their accessibility and SEO optimisation. The research methodology assumes repeatability and transparency of measurements so that the obtained results can serve as a reliable basis for further comparative analyses and practical recommendations.

3.1. Subject of research

The subject of the analysis were geoportals that host public spatial data. These services serve informational and utility purposes. They enable, among other things, viewing thematic maps, searching for plots of land, spatial analysis, and retrieving geospatial data [Król and Sroka 2023]. Geoportals are used at different levels of administration (national, provincial, district, municipal) and by various management entities (local government units, government administration, commercial providers), which makes it possible to compare them in the context of a uniform functional purpose.

The analysis included the following geoportals:

- [1] <https://polska.geoportal2.pl/>
- [2] <https://polska.e-mapa.net>
- [3] <https://drogi.gddkia.gov.pl>
- [4] <https://geoportal-krajowy.pl/na-mapie>
- [5] <https://sip.gison.pl/tomice>
- [6] <https://warszawa.e-mapa.net/>
- [7] <https://gis.um.wroc.pl>
- [8] <https://sipmapy.geopoz.poznan.pl/sipconsumer/>
- [9] <https://geoportal360.pl/map/>
- [10] <https://mapa.inspire-hub.pl/> (accessed on 21 July 2025)

These websites are characterised by high technical similarity. Intensive use of geodata results in significant energy consumption and a considerable load on server resources. In addition, they often adopt user-unfriendly URLs, lack a complete structure of headers, metadata or alternative descriptions, and only a few meet the criteria of the Web Content Accessibility Guidelines (WCAG) [Król 2025a]. A preliminary review of the services revealed that none of them declare the use of green hosting or CO₂ emission compensation practices, which may translate into a suboptimal carbon footprint. Considering the repeatability of technologies, functions and limitations, it was assumed that the analysed geoportals form a coherent and comparable set of websites. The common features of these platforms make them objective material for comparative analyses aimed at developing ecological standards for the design and maintenance of public geoportals in Poland.

3.2. Research tools and model

The research was conducted between 21 and 23 July 2025. It involved analysing the homepages of the aforementioned geoportals. A total of 15 indicators were included in the quantitative and descriptive research, with 12 environmental indicators and 3 technical SEO indicators (DCR, Carbon Rating; Carbon Footprint), which are listed in detail in the table provided in the data repository. The statistical summaries omit indicators whose values are expressed using letters. A total of 150 manual measurements were performed under controlled technical conditions (Firefox 138.0.1 browser; Lighthouse 12.0.0 tool; no cache; network peak hours).

A set of independent tools was used for the measurements, including: Ecograder, Website Carbon Calculator, Digital Beacon, Kastor Green, as well as the author's own GPT agent, i.e. Green Web Evaluator AI (GWA AI). SEO audit tools, i.e. Google Lighthouse and RankMatch, were also employed. These tools enabled the determination of selected quality indicators, including: Ecograder Score, Carbon Rating, Carbon Footprint, EcoImpact Score, CO₂ emissions per page load (g), data transfer volume

(MB), as well as accessibility and SEO optimisation indicators such as Lighthouse SEO Score Mobile and SEO Score. The results were presented in both numerical and graphical form, which made direct comparison of the geoportals possible. The set of tools used enabled a detailed analysis of the environmental impact of the websites under study and an assessment of their compliance with sustainable digital service design standards.

3.3. Specification of GWA AI

Green Web Evaluator (GWA) was designed as a GPT agent operating in OpenAI's ChatGPT Plus environment. The tool utilises the Generative Pre-trained Transformer (GPT) architecture in the form of custom instances (Custom GPT), configured by users as personalised GPT agents. This study utilised the GPT-4-turbo language model, whose knowledge base covers resources available until June 2024. It should be emphasised that all results obtained using Green Web Evaluator are expert interpretations generated by the GPT-4-turbo model and are based solely on public, widely available sources of information. GWA was designed to analyse websites and web applications in terms of their environmental impact and compliance with sustainability principles.

Green Web Evaluator operates in an environment powered by a Conversational User Interface (CUI), enabling interactive text communication and access to current web resources via a built-in browser module. The tool is a custom instance of the GPT-4-turbo model (Custom GPT), configured as an expert analytical solution dedicated to auditing websites and web applications. GWE's functionality is based on a structured analytical method rather than automatic real-time measurements. The tool does not integrate directly with external APIs, but uses available technical indicators and quality criteria to run a unified analysis of websites and web applications.

The audit conducted with the GWE tool assigns a score to each analysed website in five areas:

- 1) performance,
- 2) green hosting,
- 3) resource optimisation,
- 4) digital accessibility,
- 5) SEO compliance.

Each component is rated on a scale of 0 to 20 points, giving a total final score ranging from 0 to 100 points. The performance criterion includes, among other things, the number and size of HTTP requests, the volume of components (MB), and the presence or absence of caching and conditional loading mechanisms. The degree of resource optimisation is assessed on the basis of such parameters as the compression techniques used, high-efficiency image formats and the quality of the source code. Accessibility criteria refer to compliance with the Web Content Accessibility Guidelines (WCAG), while the SEO audit includes, i.e., the analysis of metadata, URLs, links and content.

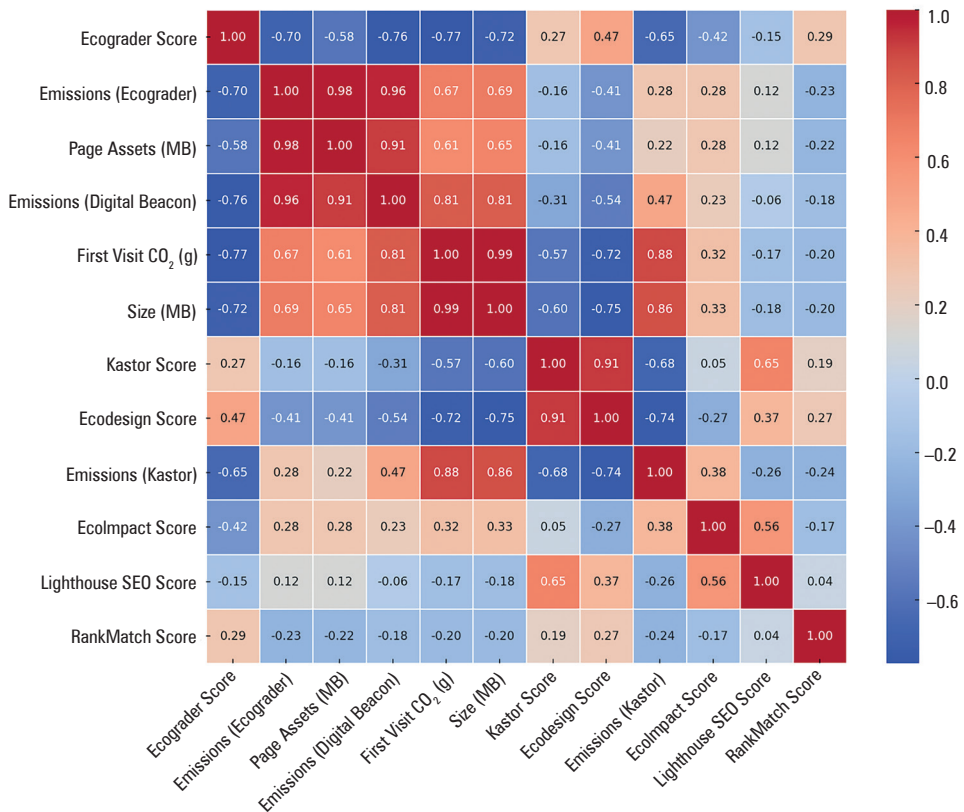
4. Results

The analysis found clear differences between the geoportals tested in terms of their potential environmental impact. The average Ecograder score was 59.8 points, with the highest score achieved by geoportal [1] with 76 points and the lowest score recorded for geoportal [10] with 44 points. The average CO₂ emissions per page load, according to Ecograder, was 1.11 grams of CO₂, while according to the Digital Beacon methodology, it was 0.78 grams. These discrepancies underline the importance of multi-tool emission measurement (so-called cross-validation). The average size of the website resources was approximately 3 MB, which generates a relatively high data transmission and energy load, although it should not be considered extremely high. The largest discrepancies were found in CO₂ emissions according to Kastor Green, i.e. from 0.17 to 2.95 g, which suggests a large discrepancy in resource optimisation and code structure. In turn, the average SEO scores, i.e. 87.8 (Lighthouse) and 52.6 (RankMatch), indicate a moderate level of compliance of geoportals with good SEO practices. The results show that most of the analysed geoportals require modernisation measures aimed at improving resource optimisation, implementing green hosting solutions and reducing their carbon footprint.

The letter grades indicate a generally low level of environmental impact optimisation of the analysed geoportals. In Ecograder (DCR), class E dominates (9/10 geoportals), with a single D result, confirming significant reserves in the area of performance improvement and resource optimisation. The Website Carbon Calculator (Carbon rating) showed greater diversity (2×C, 3×D, 2×E, 3×F), but half of the websites fall into the lowest ranges of D–F. The Digital Beacon application (Carbon footprint) confirmed the relatively high carbon footprint of the analysed websites (6×F, 1×D, 3×C). Class E in audits such as Ecograder, Website Carbon Calculator and Digital Beacon indicates websites with low environmental efficiency – with a large volume of resources, high data transfer, multiple HTTP requests and extended loading times. Such websites generate a significant carbon footprint each time they are loaded in a web browser window and thus demand the implementation of basic modernisation measures, such as code compression and minification, resource caching, graphics optimisation, and a switch to hosting powered by renewable energy sources.

An analysis of the correlation between environmental and technical indicators revealed several significant correlations. The strongest positive correlation occurs between the size of page assets, their physical size, and CO₂ emissions during the first load – correlation coefficients exceed 0.95 (Fig. 1). This confirms that larger pages generate a proportionally higher carbon footprint. Whereas, the Ecograder Score is strongly negatively correlated with emissions measured by both Ecograder and Digital Beacon (from -0.85 to -0.88), supporting its usefulness as a synthetic measure of the environmental impact of websites.

SEO indicators, such as Lighthouse Score and RankMatch Score, do not show significant correlations with CO₂ emissions, which suggests that high SEO optimisation is not directly correlated with lower environmental impact (in the adopted research model).



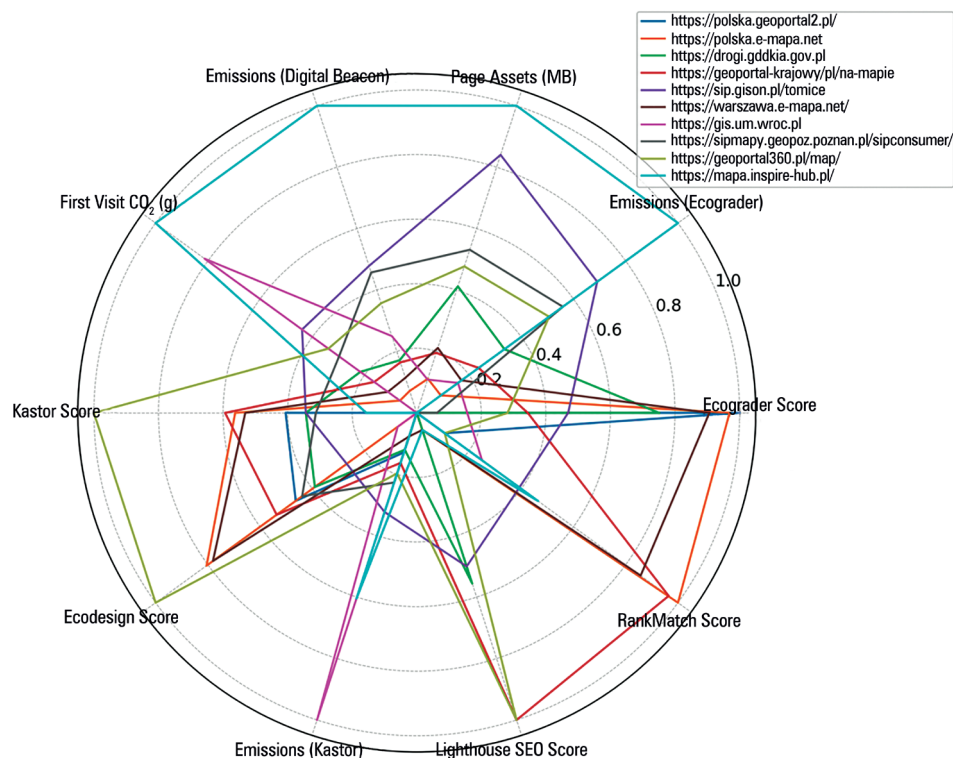
Source: Author's own study using GWA

Fig. 1. Correlation matrix between chosen environmental and technical indicators. Indicators whose values are expressed using letters have been ignored

The moderate correlation observed between the Ecodesign Score and the EcoImpact Score may indicate a partial overlap in the evaluation criteria, while also highlighting differences in the applied methodology. These results confirm that CO₂ emissions are more strongly determined by technical factors, such as the volume and structure of the transferred resources, than by the quality of SEO optimisation.

The radar chart (Fig. 2) shows a comparison of ten public geoportals based on ten indicators related to environmental performance, accessibility and website optimisation. Because the data had different units and scales, it was necessary to bring them into a common range so that they could be clearly compared on a single chart. Each portal is represented by a separate curve, and the data has been normalised (min-max normalisation on a scale of 0–1), allowing values to be compared regardless of the unit of measurement.

Analysis of the chart exposed significant differences between the surveyed websites. Some websites achieve high values on SEO indicators (e.g. Lighthouse



Source: Author's own study

Fig. 2. Comparison of geoportals based on chosen environmental and technical performance indicators. Indicators whose values are expressed using letters have been ignored. Source: own study using GWA

Score) or have relatively low CO₂ emissions when loading pages, but at the same time score lower in the area of resource optimisation or overall eco-efficiency (e.g. Ecograder or Kastor). Websites that consistently reach moderate results in all categories were also identified, which may indicate a balanced, albeit not fully effective, approach to optimisation.

The observed differences indicate that there is no standardised model of a service characterised by high environmental efficiency in all analysed areas among the set of studied geoportals. These differences may result from different design priorities, diverse institutional backgrounds or varying levels of awareness of green design principles. As a consequence, this points to the need to develop harmonised standards for the design of public sector websites that will reduce their carbon footprint and increase the environmental performance of digital services.

5. Discussion

The dynamic developments in digital technologies have brought significant benefits to public services, but they also come with increasing pressure on the environment. The internet is currently responsible for approximately 3.8% of global CO₂ emissions. Therefore, in response to the challenges of sustainable development, it is becoming necessary to take environmental aspects into account in UI/UX design [Kiourtis et al. 2024]. However, there are no universally applicable design standards, legal regulations or awareness in this regard. The elaboration of educational tools and practical guidelines can support designers in creating more energy-efficient solutions, contributing to the creation of an environmentally friendly Internet [Sarapure and Kumar 2024].

The results confirm that public geoportals, despite their growing informational role, are not fully adapted to environmentally friendly design standards. The recognised shortcomings in code optimisation, green hosting, and low compliance with WCAG and SEO guidelines confirm the trends already signalled in the literature [Król 2025b, Riabova 2025]. Compared to e-commerce, media or educational websites [Freitag et al. 2021], geoportals feature significantly larger resources and more intensive data transfer, which directly translates into a higher carbon footprint. Lower ratings in SEO and WCAG compliance may, in turn, result from technical constraints and the specific nature of public institutions, which less frequently implement optimisation solutions typical of the private sector [Riabova 2025]. However, in the face of growing climate challenges, it is worth remembering that every activity in the digital ecosystem, from opening a website to using web applications, involves the use of servers and data transmission, which generate CO₂ emissions. The results of existing research indicate that responsible design decisions, such as limiting the number of HTTP requests, code minimification, graphics compression, and simplified navigation architecture, can lead to real reductions in energy consumption and CO₂ emissions. Web designers have a significant impact on reducing the negative environmental impact of digital products and can contribute to the achievement of sustainable development goals.

An important added value of this study is the use of comparative analysis based on several independent tools, which allowed for a better understanding of the multidimensional nature of the analysed issues. A similar approach was presented by Sala et al. [2024], who pointed to discrepancies in the results obtained from measurements using different tools for monitoring CO₂ emissions in real time. The results are consistent with the findings of Pachilakis et al. [2023], who showed that elements invisible to the user, such as programming libraries and so-called tracking scripts, can reduce performance and significantly increase CO₂ emissions. In turn, an analysis of university websites conducted by Król [2025b] revealed that the average size of university information pages exceeds 5 MB, and CO₂ emissions per page load often fluctuate around 2–3 g. In contrast, the results of the audit of public geoportals presented in this paper show an average page size of around 3 MB and emissions of 0.17–2.95 g CO₂ depending on the used technology. This means that despite their specific nature, geoportals do not always generate a larger carbon footprint than information websites. The differences may stem

from different design priorities. In the case of university websites, extensive multimedia content may require optimisation, while in the case of geoportals – dynamic map rendering and large geodata sets.

The analysis allows us to draw conclusions about the impact of domain configuration and redirection mechanisms on the environmental performance of geoportals. The existence of multi-stage redirects, especially those that are not optimised or lead to external resources, significantly increases page loading time and thus increases energy consumption on both the user and server sides. This is related to the so-called parameterisation of network resource addresses and URL optimisation [Król 2015]. An example of this phenomenon are geoportals that refer to resources located deep within the URL path [Król 2025a]. Such solutions, if not supported by caching mechanisms or content delivery networks (CDNs), generate additional HTTP requests and increase the CO₂ emissions attributed to a single page view. As to designing sustainable digital services, it is recommended to avoid unnecessary redirects, use direct and optimised URLs, and implement techniques that reduce server response time, which directly translates into a reduction in the carbon footprint related to user interaction with the service.

The analysis conducted as part of this study provided answers to the set research questions. With regard to RQ1, concerning the impact of the technical architecture and data structure of geoportals on their carbon footprint, the audit found clear correlations between the size of resources (including JS components, CSS and image files), HTML code structure and the occurrence of redirects, and the level of CO₂ emissions generated during page loading. Geoportals with a more complex and unoptimised structure had a significantly higher carbon footprint, reaching over 2.5 g CO₂ per load, which demonstrates the key importance of design decisions made at the technical level. With regard to RQ2, the scope of the study did not include qualitative identification of barriers to the implementation of green UX/UI practices. Therefore, it is not possible to draw direct and unambiguous conclusions about the reasons for the limited use of Green SEO practices. However, from the observations made during the research, it can be indirectly inferred that technical and organisational factors may be relevant, such as the complexity of system architecture, the prioritisation of usability at the expense of environmental aspects, or the lack of clear industry guidelines. This implies that implementing sustainable design principles in geoportals demands not only infrastructure upgrades, but also the development of standards and tools to support public institutions in integrating environmental criteria into design and management processes. An additional problem is the lack of clear guidelines and standards for the ecological optimisation of digital services in the public sector. In consequence, even technologically advanced geoportals do not meet environmental performance criteria, despite the availability of solutions that facilitate a significant reduction in CO₂ emissions without compromising the quality of provided services.

6. Conclusions

The results of the study proved that the technical structure of geoportals significantly affects their impact on the environment, revealing key factors shaping their performance. The analysis based on standardised quality indicators allowed for the identification of both good practices and areas requiring further optimisation. The use of statistical methods, including correlation analysis, has expanded knowledge about sustainable digital development, until now rarely referred to in relation to public administration platforms. These results open up a discussion on the responsibility of public institutions for the environmental impact of digital development and provide a starting point for the development of industry standards for the design of sustainable geoinformation services.

The findings indicate that the current technological state of many geoportals does not fully meet the current standards for environmentally friendly website design. At the same time, the analysis identified specific measures, such as eliminating unnecessary redirects, optimising resources and implementing green hosting, which can bring measurable environmental benefits. Although the literature on the subject focuses mainly on commercial websites, the study indicates that public institutions should actively participate in the process of digital transformation aimed at sustainable development, motivated not only by ethical considerations, but also by reputational and functional factors. The varied results of the Green SEO audit in relation to the analysed geoportals may be a consequence of overlapping technological and organisational conditions. Some websites provide extensive volumes of geospatial data, resulting in a significant amount of resources and intensive data transfer. In some cases, it was found that advanced optimisation mechanisms such as compression, minification, lazy loading and caching were not implemented, leading to increased CO₂ emissions and longer page loading times. Furthermore, not all geoportals show signs of using green hosting, which is understood as infrastructure powered by renewable energy sources or that declares climate neutrality. This may be due to limited transparency on the part of hosting providers or a lack of integration of such practices into institutional policies. In addition, in several cases, accessibility and SEO deficiencies were identified, which may have affected the audit result. However, the identified factors do not clearly demonstrate the low quality of the assessed websites, but rather the lack of sustainable design standards, due to budgetary and technological constraints or the lack of dedicated guidelines for public institutions.

Practical implications and limitations of the study

The results of this study have important practical implications for designers, administrators and decision-makers responsible for the maintenance and development of public geoportals. First and foremost, they emphasise the need to take environmental aspects into account at the design and modernisation stage of websites. This concerns in particular the introduction of compression, minification and source code optimisation

techniques, the elimination of unnecessary redirects, and the use of hosting solutions based on renewable energy or guaranteeing climate neutrality. These measures can directly contribute to reducing the carbon footprint, improving website performance and enhancing the user experience. In addition, the development and implementation of national guidelines for green design of digital services in the public sector could significantly accelerate the transition to sustainable digital development, ensuring consistency and comparability of the applied solutions. The results of the study can also be used to create benchmarking tools that support the monitoring and systematic assessment of the environmental performance of digital services per unit of time. This would contribute to the long-term improvement of the quality of the public sector's digital infrastructure. However, certain limitations of this study should be noted. Firstly, the audit was partly expert-based and relied solely on publicly available data, without access to server infrastructure or information on actual user traffic. Secondly, the interpretation of the results was based on the assumptions of selected assessment models (Ecograder, Kastor, Digital Beacon), which differ in their measurement methodology. Finally, the relatively small number of analysed websites limits the possibility of fully generalising the results to the entire public administration sector. The limitations of the study point to the necessity of extending the analysis to a larger set of geoportals, and combining technical and usage data, as it will provide a more complete picture of their impact on the environment. Further research is also necessary to develop general design guidelines and policies to support the development of sustainable geoinformation services.

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