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Assessment of the ecological footprint of smart cities through sustainable development indicators

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Оценка на екологичния отпечатък на интелигентните градове чрез показатели за устойчиво развитие

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Abstract: The concept of a "smart city" should not be associated solely with a "digital city". A city can be classified as a smart city if economic activities, mobility, environmental resources, relationships between people, housing policy and the way in which technological innovations are implemented are intelligently managed. The aim of the study is to establish the ecological footprint of smart cities through sustainable development indicators. The results show that Carbon dioxide (CO_2) emissions are associated with emissions from industrial processes, as well as from the burning of fossil fuels. The conclusion that can be reached is that although Sofia has lower CO_2 emissions per capita than Amsterdam in 2024, the trend is worrying, as emissions are increasing on an annual basis, while for Amsterdam and Vienna they are decreasing. For Sofia, the green area per capita is found to be 9 square meters per person. A comparison of the three cities shows that Vienna is the city with the largest amount of green space per capita. The capital of Austria is distinguished by over 55% green space of its total area, which means that each resident has an average of 120 square meters of green space, including parks, gardens, and other green areas. Annual average PM concentrations in Sofia are significantly higher than those recommended by the WHO. The data analysis shows that among the three cities studied, the average annual PM10 level is highest in Sofia, followed by Vienna. The indicator in Amsterdam has a significantly lower value.

Key words: smart, city, digital, sustainable, development, ecological, footprint

Резюме: Концепцията за „интелигентен град“ не бива да се свързва единствено с „дигитален град“. Един град може да бъде класифициран като интелигентен, ако икономическите дейности, мобилността, екологичните ресурси, взаимоотношенията между хората, жилищната политика и начинът, по който се внедряват технологичните иновации, се управляват интелигентно. Целта на изследването е да се установи екологичният отпечатък на интелигентните градове чрез показатели за устойчиво развитие. Резултатите показват, че емисиите на въглероден диоксид (CO_2) са свързани с емисии от промишлени процеси, както и от изгарянето на изкопаеми горива. Заключението, до което може да се стигне, е, че въпреки че София има по-ниски емисии на CO_2 на глава от населението от Амстердам през 2024 г., тенденцията е тревожна, тъй като емисиите се увеличават на годишна база, докато за Амстердам и Виена те намаляват. За София зелената площ на глава от населението е 9 квадратни метра на човек. Сравнението на трите града показва, че Виена е градът с най-голямо

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количество зелени площи на глава от населението. Столицата на Австрия се отличава с над 55% зелени площи от общата си площ, което означава, че на всеки жител се падат средно 120 квадратни метра зелени площи, включително паркове, градини и други зелени площи. Средногодишните концентрации на PM в София са значително по-високи от препоръчителните от СЗО. Анализът на данните показва, че сред трите изследвани града средногодишното ниво на PM10 е най-високо в София, следвана от Виена. Показателят в Амстердам има значително по-ниска стойност.

Ключови думи: интелигентен, град, дигитален, устойчив, развитие, екологичен, отпечатък

Introduction

The need for sustainable development and increasing urbanisation has led to significant changes in cities worldwide in recent years. Increasing environmental challenges and population growth have identified technology as a key factor in creating smart cities, defined as modern and advanced urban spaces that use technological innovations to achieve more efficient resource consumption and improve the overall quality of life of citizens. The use of technology in smart cities leads to the optimization of various aspects of the urban environment, including energy efficiency, traffic management, waste management, water supply and communication with citizens. The goals of smart cities are aimed, on the one hand, at creating more efficient and sustainable public systems to improve and facilitate the lives of citizens, and on the other hand, at reducing the ecological footprint of cities. The benefits of smart cities are both for their residents and for the environment and are manifested in several aspects. First, smart cities contribute to reducing carbon emissions, which is key in the fight against climate change. Second, the optimised use of resources leads to lower costs for managing cities, which can also reflect on reducing the amount of taxes and fees paid by citizens. Third, smart cities contribute to improving the quality of life of citizens, because they benefit from cleaner air, more efficient transport and better conditions for recreation.

Smart cities have a crucial impact on achieving sustainable development. In recent decades, due to the increase in urban population, rising production and consumption, as well as the activities carried out by people, the concept of sustainability has become increasingly important. Sustainable development is associated with such development that meets the needs of the present generation without creating risks for future generations to meet their needs [Dogan, 2024]. The concept of sustainable development envisages economic growth that can meet the needs of modern society for well-being (with all its socio-demographic and health characteristics) in the long term, without depriving future generations of the opportunity to meet their needs [Mensah, 2019]. Specifically, sustainable development implies choosing and promoting strategies for economic development that are consistent with the protection and improvement of the environment and the biological balance of the Earth [Cernev, Fenner, 2020]. Sustainable development has various aspects - managerial, economic, ecological, and social. It is a striving for a policy and lifestyle of the population and, above all, a state of the economy in which waste-free technologies are used, it is based on the use of renewable raw materials, it relies on recycling, and the goal is for the exploitation of natural resources not to change the parameters that affect human life. The idea of sustainability implies that economic growth, social cohesion and environmental protection go hand in hand and complement each other [Shi et al., 2019].

Due to the development of technology, the increase in the population in cities, the changing needs of people and the economic and environmental transformation, smart urbanization is gaining more importance [Sharifi et al., 2024]. The article aims to empirically verify the existence of a relationship between the ecological footprint of smart cities and sustainable development.

1. Literature review

1.1. Definitions of smart city and ecological footprint

Smart cities are among the most current and promising directions for the sustainable development of modern urbanised societies. They embody not only a vision for the future, but also a means to address key global and local challenges. In the context of accelerated urbanisation, increasing demands for environmental sustainability and the need for effective resource management, the concept of smart cities is being established as a strategic solution [Russo, 2025]. The term smart city, in a broad sense, is related to an urban environment that can actively act to improve the quality of life of its inhabitants. A smart city manages to combine and meet the needs of its inhabitants, companies and institutions, thanks to the innovative use of information and communication technologies, in the fields of communications, mobility, environment and energy efficiency. It is a city where there is a high level of quality of life, where urban spaces can help the implementation of projects to be implemented faster, easier and save time [Tarek et al., 2025]. All this would contribute to improving the environment.

The main technologies that make cities smart are [Sharma et al., 2023]:

- Internet of Things (IoT): IoT devices are at the heart of smart cities because they connect different components of city infrastructure, such as sensors, appliances, etc., to collect and analyse data in real time. This allows for more efficient resource management and faster response to different situations. For example, smart street lights can adjust their brightness depending on the passage of people or vehicles, which reduces energy consumption.
- Smart energy grids: Renewable energy sources such as solar and wind power are at the heart of sustainable cities. Smart energy grids allow for more efficient distribution of electricity and management of peak loads, and provide the opportunity for citizens to produce and sell their own energy, such as through solar panels, which reduces dependence on traditional energy sources.
- Waste management: Smart waste management systems use sensors to monitor the level of filling of containers and optimise the routes of garbage collection trucks. This not only reduces carbon emissions but also the costs of waste management. It is also important to specify that smart cities encourage recycling and composting through innovative solutions such as automated waste sorting stations.
- Transport technologies: Smart cities rely on sustainable transport solutions, such as electric vehicles, car and bike sharing, as well as high-efficiency mass urban transport. Traffic management systems based on artificial intelligence optimise traffic flow and reduce congestion, which contributes to cleaner air and less stress for citizens.
- Smart buildings: Buildings in smart cities are equipped with intelligent energy management systems, heating, ventilation and lighting. They use real-time data to optimise their operation and minimise energy consumption. Green roofs and facades, as well as technologies for rainwater collection and wastewater recycling, are also part of sustainable urban solutions.
- Digitalisation of city services: In smart cities, citizens can benefit from digital services such as e-governance, online bill payment, and mobile applications for reporting

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infrastructure issues. This not only makes their lives easier but also reduces the need for physical resources such as paper and time spent processing documents.

Related to the characteristics of smart cities is the ecological footprint. In essence, the ecological footprint is one way of measuring sustainability, which refers to the ability of a population to sustain itself in the present without compromising this ability for the future. Environmental sustainability occurs when a population can maintain a certain lifestyle indefinitely while meeting the demands placed on the environment [Chulenyov et al., 2024]. The ecological footprint measures how our behaviour and consumption affect the environment, whether we live sustainably or at the expense of future generations. The index shows how sustainable our lifestyle is, since all the raw materials we eat, live with, and travel with need space on the earth to regenerate. At the same time, nature needs resources to process our waste. The ecological footprint is therefore a measure of the area of land needed by one person. It is measured in global hectares (GHA). The main factors that influence the ecological footprint are human activities that lead to global warming and air pollution, such as practices for using cars that emit harmful gases or the use of pesticides [Ozdamar &Yigit, 2024].

Smart cities have a significant contribution to reducing the ecological footprint. The main prerequisites for the positive impact of smart cities are the use of intelligent electrical and flexible networks, allowing for more efficient use of energy and the inclusion of renewable sources, promoting the transition to a circular economy, real-time monitoring of environmental indicators and taking corrective actions, etc. [OECD, 2023].

The concept of a “smart city” should not be associated solely with a “digital city”. A city can be classified as a smart city if economic activities, mobility, environmental resources, relationships between people, housing policy and the way in which technological innovations are implemented are intelligently managed [Russo, 2025]. A city is “smart” when investments in human and social capital and traditional urban systems - infrastructures (transport) and modern fuel (ICT), sustainable economic development contribute to a higher quality of life, through wise management of natural resources and participation of society [Karatzimas, 2024]. A “smart” city should not be associated solely with the availability of information and communication infrastructure, but it includes the role of human capital, the social sphere (education, culture, etc.), as well as the environmental sector as a major factor in its growth. Smart cities combine innovative technologies, sustainable practices and intelligent governance to improve not only the daily lives of their citizens but also the overall urban environment [Martinez & Mahajan, 2023]. They include integrated transport, energy, water and waste management systems that work in sync to achieve greater efficiency and sustainability. They provide a platform to foster innovation, incorporating smart solutions such as the Internet of Things (IoT), big data and artificial intelligence (AI) to meet the dynamic needs of modern society [Hui et al., 2023]. It is important to clarify that to create smart cities, it is necessary to undertake activities regarding mobility technologies and services, sustainable development, citizen participation, facilitating access to services, effective communication and optimizing resources.

A smart city can be either an entire city or a specific area of a city that uses electronic and technological infrastructure, such as information and communication technologies, to collect data and make real-time analyses, to provide certain important services that solve urban problems. With the growing need for sustainable cities in the global context of climate change, the concept of a smart city has been placed on the environment and the surrounding climate, including the interaction between technology and nature, promoting the integration of climate strategies and

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citizen participation to adapt to climate impacts. The main goal of a smart city is to improve well-being and adaptation to climate change by providing services that support each of its residents. Smart cities improve the daily activities of the city, such as public transport and mobility, electricity and water supply, sewage systems, etc. Using this data, local authorities can extract useful information and provide effective solutions to correct prevailing urban problems. Technologies have a significant impact on reducing the ecological footprint. Effect of optimizing energy/resource usage in line with the actual travel of people and goods in all situations, such as business operations, daily life and travel behaviour, realizing a decarbonized society.

1.2. Existing Models and Indices

There are various models and indicators for measuring sustainability and environmental footprint. One of the most widely used is Leadership in Energy and Environmental Design (LEED), a globally recognised green building certification program [Vosoughkhosravi et al., 2022]. To obtain this certification, several specific requirements and norms are required, and buildings that receive it increase their price many times. As a green building certification system developed by the United States Green Building Council (USGBC), LEED is the most widely used sustainability certification program for buildings. The main benefits of LEED are for [Leite Ribeiro et al., 2025]:

- Business - LEED-certified buildings have a higher resale value and lower operating costs than buildings without LEED certification. LEED is an important strategy for achieving environmental, social and governance (ESG) goals, decarbonization and sustainability.
- Occupants - LEED-certified buildings focus on the well-being and health of their occupants, offering healthier and better-quality indoor spaces, while also addressing community and public health.
- The environment – LEED certified buildings use less energy and water, utilize renewable energy and fewer resources, create less waste, and preserve land and habitats.

Another essential indicator is ISO 37120, which is an international standard providing a set of indicators for measuring the quality of life and the provision of urban services. The standard is intended for cities, municipalities and local authorities who want to compare and improve their performance. ISO 37120 uses various smart city indicators, which are grouped as core and standardized (46 in number), supporting (54 in number), and profile (35 in number). The core and supplementary indicators are divided into different groups, such as economy, education, energy, environment, finance, government, response to fires and various crises, health, recreation, transport, telecommunications, urban planning, water supply and water loss. For example, in the environment group, the core indicators used are fine particulate matter concentration (PM2.5), particulate matter concentration (PM10) and greenhouse gas emissions, measured in tons per capita. As supplementary indicators, the standard introduces NO2 (nitrogen dioxide) concentration, SO2 (sulphur dioxide) concentration, O3 (ozone) concentration, Noise pollution, Percentage change in number of native species [Midor & Plaza, 2020].

At their core, the various methods and indicators aim to establish the effectiveness of the sustainability strategies used in smart cities. In addition to LEED and ISO 37120, indicators used to assess the impact on the ecological footprint are also an analysis of energy consumption, air quality and waste management. Research methodologies used are also aimed at the amount of green revenues received, smart strategies used to improve the quality of life of the population, energy efficiency, urban sustainability, environmental sustainability, etc. [Oyadeyi, 2025].

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2. Methodology

The aim of the study is to establish the ecological footprint of smart cities through sustainable development indicators.

The material used to conduct the study includes scientific publications and studies published on a global issue to establish the scope of topics related to the impact of smart cities on the ecological footprint. Keywords such as "ecological footprint", "smart cities", "sustainable development", "indicators", etc., were used to search. The word "history" was additionally included to add a historical perspective to the development of the problem. The following criteria were defined for including publications in the thematic analysis: full-text publications created in English or Bulgarian, published in refereed scientific journals, indicating the specified keywords and expressions. The title, abstract, keywords, and sources of the articles that met the criteria for inclusion in the review were reviewed, from which additional suitable publications were extracted. Additional sources for data collection are Eurostat, EEA, Worldometers, Statista, and Our World in Data, as well as national and municipal reports. Data for the period 2020-2024 has been selected. This ensures comparability and provides an analysis of the short-term development of CO_2 emissions, air pollution, energy consumption and urban green spaces.

The methods used in the study are analysis, synthesis, induction, and deduction.

The indicators used are:

- CO_2/inhabitant (CO_2 emissions per capita) - shows the scale of the carbon footprint;
- green areas/inhabitant (green area per capita) - indicator of ecological sustainability and quality of the urban environment;
- PM10 - indicator reflecting air quality and its implications for public health;
- energy efficiency - indicator reflecting the level of energy dependence and the degree of efficiency.

The objects of analysis are the cities of Sofia, Amsterdam, Vienna, which will be compared according to environmental indicators. They were selected as cities with different profiles – Sofia being a fast-growing Eastern European capital with its own ecological issues, Amsterdam being an example of advanced sustainable management and Vienna having a large coverage of green areas and powerful policies regarding energy efficiency. This option enables comparison of varying urban settings.

A key limitation is that the availability and methodology of national statistics vary, potentially affecting comparability.

3. Results

Carbon dioxide (CO_2) emissions are associated with emissions from industrial processes, as well as from the burning of fossil fuels. Emissions are generated from heating, transportation and electricity generation. Figure 1 presents a comparison between CO_2 emissions per capita in the three cities studied.

The comparison between the three cities shows that Amsterdam has the highest CO_2 emissions per capita, followed by Sofia and Vienna. Although Sofia’s 2024 value is lower than that of Amsterdam, the trajectory remains concerning. Based on analyses of available municipal and national data, Sofia (and Bulgaria) exhibit a flat-to-increasing trend in CO_2 emissions per capita in recent years, contrasting sharply with the established annual downward tendencies observed in Amsterdam and Vienna (and their respective national contexts) [Joint Research Centre (JRC) & International Energy Agency (IEA), 2024; Planbureau voor de Leefomgeving (PBL), 2024].

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The conclusion reached is that the increasing trend in Sofia is worrying, as it contradicts the established goals for decarbonisation. It should be noted that data availability and reporting consistency differ across city and national inventories; therefore, country-level per capita data were used as proxies to establish recent trends where consistent city-level time series were unavailable.

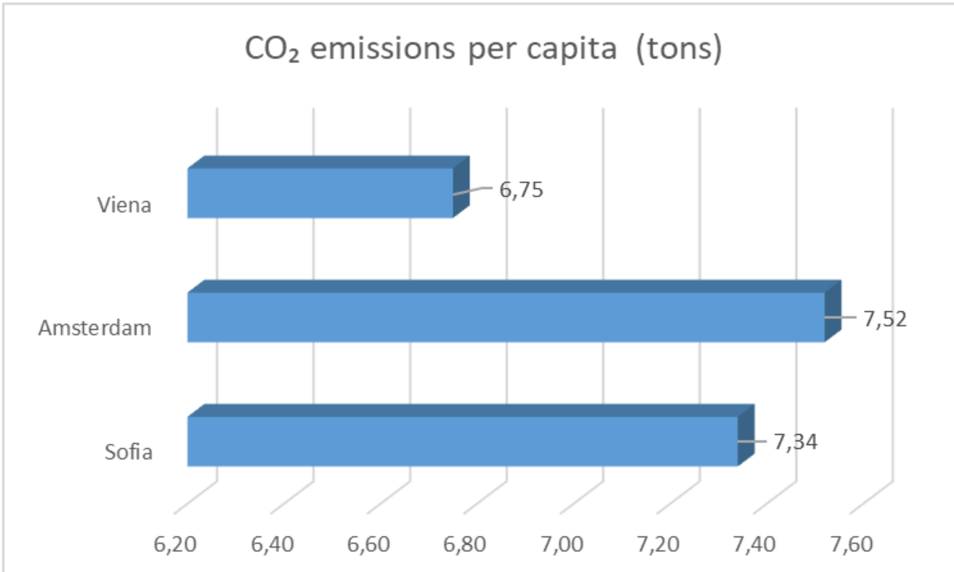

Fig. 1. CO_2 emissions per capita in Sofia, Amsterdam and Vienna [Wordometors, 2025; Statista, 2025]

Figure 2 presents a comparison between green areas per capita in the three cities studied. Green spaces in cities are a key indicator measuring the coverage of green spaces per inhabitant. Analyzing the indicator allows identifying the main problems related to the living environment and ecosystems and taking actions to achieve balance in urban spaces. The data shows that the amount of green space per capita in cities varies greatly between neighborhoods and zones, with more peripheral areas having significantly more green space than the central city. For Sofia, the green area per capita is found to be 9 square meters per person. A comparison of the three cities shows that Vienna is the city with the largest amount of green space per capita. The capital of Austria is distinguished by over 55% green space of its total area, which means that each resident has an average of 120 square meters of green space, including parks, gardens, and other green areas. Vienna is often cited as a model for urban green space management and is considered one of the greenest cities in the world, according to various sources.

PM10 is a measure of fine particulate matter that is 10 micrometers (µm) or smaller in diameter in the air. These fine particulate matter are small enough to be inhaled into the lungs. Figure 3 presents a comparison between PM10 in the three cities studied.

The World Health Organization (WHO) says that no level of air pollution can be considered “safe” and the link between air pollution and respiratory and cardiovascular diseases is clearly established. Particulate matter with a size of 10 micrometers (PM10) or 2.5 micrometers and smaller (PM2.5) causes the most serious health problems. Annual average PM concentrations in Sofia are significantly higher than those recommended by the WHO. The data analysis shows that among the three cities studied, the average annual PM10 level is highest in Sofia, followed by Vienna. The indicator in Amsterdam has a significantly lower value.

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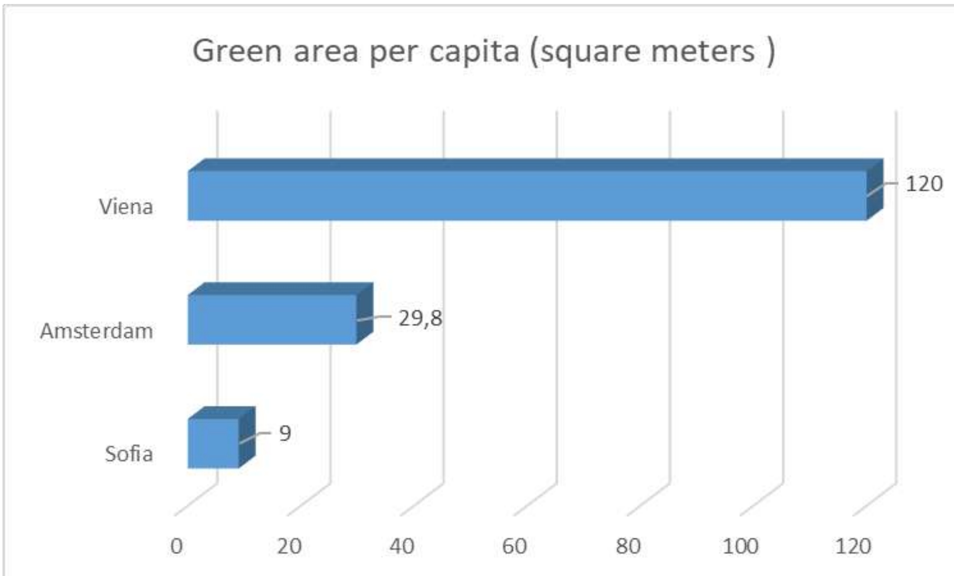

Fig. 2. Green area per capita in Sofia, Amsterdam and Vienna [Green space per inhabitant, Statista, 2024; Todorova, 2023]

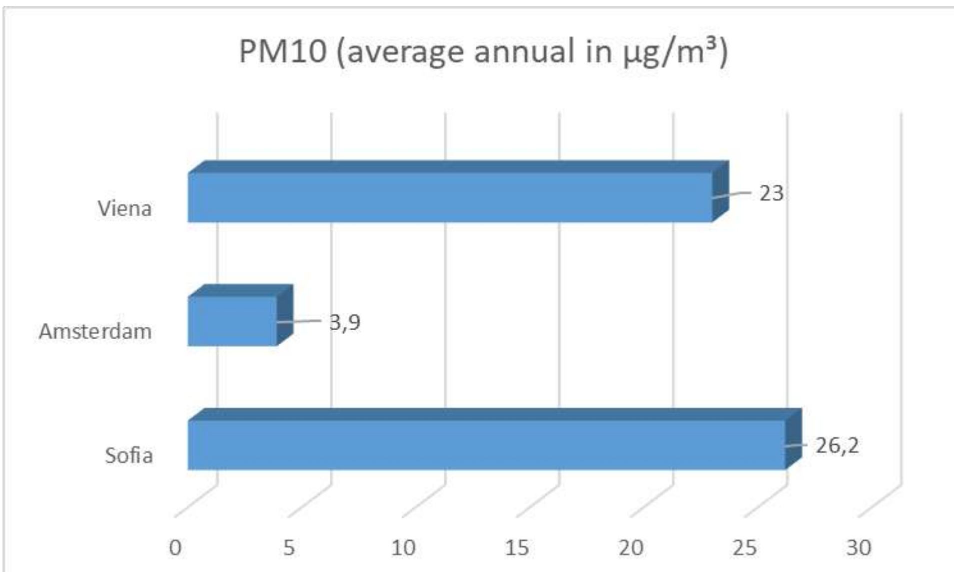

Fig. 3. PM10 in Sofia, Amsterdam and Vienna [Air quality, 2025]

Table 1 presents the results of the final energy consumption per capita in the three cities.

Table 1. Final energy consumption per capita [Primary energy consumption per capita, 2025]

City	Final energy consumption per capita
Sofia	5310 kWh
Amsterdam	6 100 kWh
Vienna	19 502 kWh

The data in the table shows that Sofia is the city with the lowest energy consumption of the three cities studied. Energy is one of the most important sectors in the country, but energy dependence is high. In Amsterdam, about 35% of final energy consumption is from private households, with about 45% of the energy used from natural gas, followed by 30% electricity [Primary energy consumption per capita, 2025]. In Vienna, energy policy is mainly focused on reducing energy consumption per capita and increasing the share of energy used from renewable energy sources. The city is also actively working to improve the energy efficiency of buildings and more effectively utilize waste technology from renewable energy sources to achieve decarbonization.

Conclusion

The study shows that we can effectively assess the ecological footprint of smart cities using a matrix of connected sustainability indicators. These include CO2 emissions, urban green spaces, air quality, and energy efficiency.

The comparison of Sofia, Amsterdam, and Vienna reveals significant differences in performance. While Sofia currently has lower CO_2 emissions per capita than Amsterdam, its trend is worrying. It has shown a stable to slightly increasing trend in recent years. This situation is made worse by the city's highest recorded PM10 levels and ongoing high energy dependence. In sharp contrast, Amsterdam and Vienna have achieved documented reductions in emissions. Vienna stands out for having a significant amount of green space per capita and good renewable energy policy. These findings suggest that the environmental impact of smart cities depends not merely on technological progress but also on the quality of governance, urban planning, and specific sustainability initiatives.

This review suggests that city planning needs to now integrate strong environmental Key Performance Indicators (KPIs) immediately. These include the expansion of green spaces, development of air quality measures, and drastically increasing renewable energy use across different sectors. Moreover, even though digital technologies can reduce the overall energy footprint, we also have to consider and manage likely risks. These include the growing energy demand of IoT infrastructure and the resultant increase in e-waste.

In conclusion, sustainability has to guide smart city development. The use of environmental indicators in decisions is key to reducing the ecological footprint, making urban use of resources more efficient, and finally enhancing the citizens' quality of life.

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