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Interdisciplinary Linkages among Sustainability Dimensions in the Context of European Cities and Regions Research

Stanislav E. Shmelev [1,*], Nathan Lefievre [2], Nadim Saadi [3] and Irina A. Shmeleva [4]

1 Environment Europe Foundation, Fluwelen Burgwal 58, The Hague Humanity Hub, 2511 CJ The Hague, The Netherlands
2 Sciences Po, 75007 Paris, France; nathan.lefievre@sciencespo.fr
3 Department of Chemical Engineering, McGill University, Montreal, QC H3A 0G4, Canada; nadim.saadi@mail.mcgill.ca
4 Institute of Design and Urban Studies, ITMO University, St. Petersburg 199034, Russia; irina_shmeleva@hotmail.com
* Correspondence: director@environmenteurope.org

Abstract: Many dimensions of urban sustainability are intricately intertwined; however, systematic assessment of those linkages is often missing. To explore the details of these interdisciplinary linkages, we employ an in-depth literature review technique coupled with a multidimensional assessment of sustainability for 1300+ cities and regions in Europe. The wealth of indicators affecting economic, smart, social and environmental dimensions are linked within a coherent framework illustrating systemic links in urban sustainability. The performance of cities is illustrated using the multidimensional framework highlighting the contributions of various factors. The spectacular performance of Stockholm, Paris, London, Gothenburg, Malmö, Munich and Hamburg are illustrated with examples. Policy recommendations are offered to make cities and regions around the world more sustainable.

Keywords: sustainable cities; urban sustainability; performance indicators; multidimensional assessment; policy recommendations

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1. Introduction

The 'Envisaging the Future of Cities' report by UN Habitat (2022) states that urbanization is deeply interrelated with multiple global challenges of climate change, social inequality and pandemics, and 'changing course to a sustainable path' is the only option to avoid future high damage or pessimistic development scenarios [1]. The urban sustainability challenge therefore demands a new and entirely interdisciplinary approach [2–6] as outlined in our research: Shmelev and Shmeleva (2009) [7] and Shmelev (2019) [8], Shmelev et. al (2018) [9], Shmelev and Shmeleva (2018) [10]. Recently, a new framework of 'New Urban Science' has been proposed by Karvonen, et al. (2021) [11] to illustrate interdisciplinary collaborations required to drive sustainable urban transformation. Interdisciplinarity has been highlighted as a top priority in conceptualization [12] and education [13] in the field of urban sustainability. Interdisciplinary methods and tools have been used in the research on urban metabolism [14], the new challenges of governing cities in the anthropocene [15] and examining the connections between vulnerability, resilience and adaptive capacity [16]. Sustainable urban planning in cities requires interdisciplinary synthesis, and interdisciplinarity today has become the focus of substantial monographs [17]. The UN Habitat 'Envisaging the Future of Cities' report posits that 'A multidimensional approach is key to an inclusive urban future' [1]. European Green Capital Award is an established framework attracting attention to the sustainability achievements of European cities [18].

Systemic urban sustainability models for cities are rare and existing models are tackling individual dimensions of urban sustainability. For instance, Purvis et al. (2022) [19]

employed a systems dynamic approach for urban sustainability, Kissinger and Stossel (2021) [20] applied a mathematical model to study the resource metabolism of cities and Chen et al. (2011) [21] built a city model that is connected to the weather forecasting model. More recent complex systems studies of cities include [22–41].

Several alternative methodologies that utilize digital technology, including smart sensors, artificial intelligence, GPS data and the data from social media, are becoming increasingly popular. For instance, Calabrese et al. (2013) [42] conducted research on urban transport choices, employing anonymized data from mobile phone networks, and Bongiorno et al. (2021) [43] used a big data approach to study movements of pedestrians in the urban environment. Yan et al. (2020) [44] applied such a big data approach to examine the effects of sharing trips on air pollution in the urban context. Nicholson et al. (2022) [45] used a similar approach to study urban green infrastructure, Legeby et al. (2021) [46] studied new lifestyle choices and habits that emerged after the pandemic and Esmaeilian et al. (2018) [47] applied smart technology to understand waste management trends in cities.

More and more, models built on multiple Key Performance Indicators (KPIs) are being created to study urban sustainability trends [48–50]. Urban ecosystem services have become the subject of new modeling applications [51]. Increasingly, the analysis of urban processes has started happening at the micro-level, on the scale of districts, as it was performed in the study by Orozco-Messana et al. (2021) [52] or Buzási and Jäger (2020) [53]. Participatory methods have been applied in e.g. [54]. However, despite the growing interest in urban sustainability and a clear preference for interdisciplinary methods, there is a tangible gap in research focusing on examining and, most importantly, quantifying through empirical analysis the multiple connections between various KPIs used to measure urban smart and sustainable performance. This article will be structured as follows. First, we will discuss the methodology that we use to examine urban sustainability. Then, based on empirical studies, we will present a structured review of the literature, accompanied by detailed tables of factors corresponding to our most recent study [55], focusing on multiple dimensions of urban sustainability. Then, to illustrate the practical application of the proposed approach, we will analyze the urban per capita CO_2 emissions model based on empirical data for 71 cities from all over the world, followed by the conclusion.

2. Methodology

The framework we have used over the years, shown in Figure 1 [56], connects several important dimensions of urban sustainability [57,58] and presents the systemic vision of multiple linkages among various aspects of urban performance. In this paper, we are expanding this approach to focus on other contributing factors to each of the dimensions (e.g., PM_{10} pollution, unemployment or innovation measures). Here we will explore the top seven European cities and regions leading on sustainability, based on a basket of 17 smart and sustainable performance criteria and the new results presented in Shmelev and Shmeleva (2023) [55]. This analysis is divided along four key dimensions of smart and sustainable development: economic, smart, social and environmental. Each dimension will be discussed using the corresponding criteria that were used in the assessment. This is carried out to understand the factors and the policies that have been put in place by leading municipalities that position them in the lead of our ranking. Overall, the top 7 cities in our assessment selected under equal weights among 1300+ cities and regions in Europe comprising our ranking [55] were Stockholm, Paris, London, Gothenburg, Malmö, Munich and Hamburg. The cities chosen represent a diverse pool of traditions, approaches to management and culture. The population and area are denoted for each city below: Stockholm (975,277 inhabitants, area of 188 km^2); Paris (2,142,366 inhabitants, area of 105.4 km^2); London (8,908,000 inhabitants, 1572 km^2); Gothenburg (583,684, 447 km^2 inhabitants); Malmö (348,601 inhabitants, area of 322.6 km^2), Munich (156,000 inhabitants, area of 310.7 km^2), and Hamburg (1,852,478 inhabitants, area of 755.2 km^2). We will denote the overall ranking of each city in the pan-European assessment in each subsequent table.

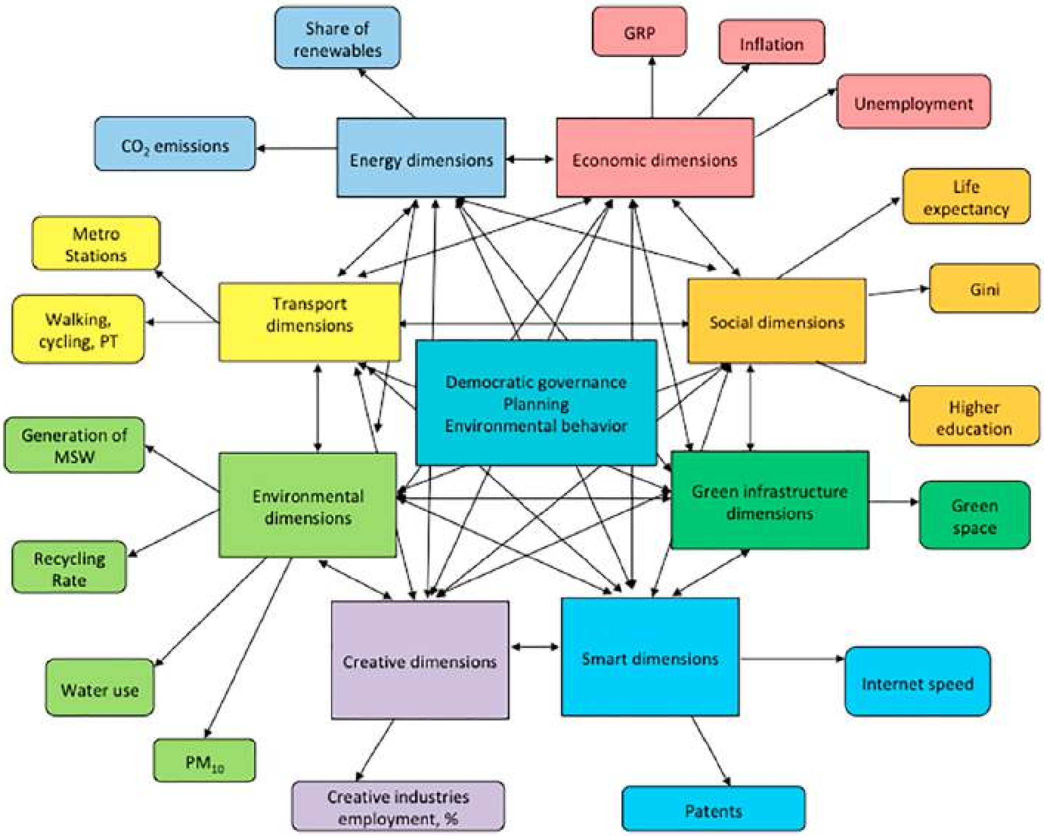

Figure 1. Conceptual framework of a smart and sustainable city assessment methodology [56].

The key research questions tackled by the present research were the following: (1) How can interdisciplinary linkages among the urban sustainability dimensions be characterized? (2) Which factors play a role in determining the performance of different cities on sustainability KPIs? How could such an approach be illustrated by a practical empirical case study?

The following map will illustrate a solid reasoning for the selection of the cities in question. They are some of the best-performing smart and sustainable cities in Europe according to our research (Figure 2). As is amply illustrated by Figure 2, the most sustainable cities and regions in Europe are represented by the shades of blue and orange color, the darker blue comprising the most sustainable. We refer the interested reader to our previous paper for a detailed explanation of how the ranking of 1300+ cities and regions was performed. We just need to emphasize here that the assessment was performed using the 17 carefully selected KPIs comprising economic (gross regional product, GRP, in current million euros, GDP per capita, consumer price inflation, unemployment), smart (number of patents per 1000 inhabitants, number of underground stations per million people, and creative industries employment), social (life expectancy at birth, share of population aged 25–64 with higher education, and Gini index of income inequality) and environmental indicators (CO_2 per capita, average annual PM10 pollution, share of renewables in the energy mix, domestic water consumption, municipal solid waste generation, recycling rate). It is very clear from Figure 2 that the Swedish municipalities of Stockholm, Gothenburg and Malmö are some of the most sustainable, as are the selected boroughs of London, the city of Paris and the selected German cities of Munich and Hamburg. It is important to mention that no article could include a detailed analysis of all 1300 cities and regions in terms of determinants of their performance, so we limited our analysis in this paper to the chosen seven cities. The subsequent analysis presents the potential explanatory variables for all the smart and sustainable dimensions in our assessment, presenting a highly structured literature review. The paper goes much further in offering an empirical case study, illustrating the application of econometric methodology to explain the differences in performance on per capita CO_2 emissions among the cities in question.

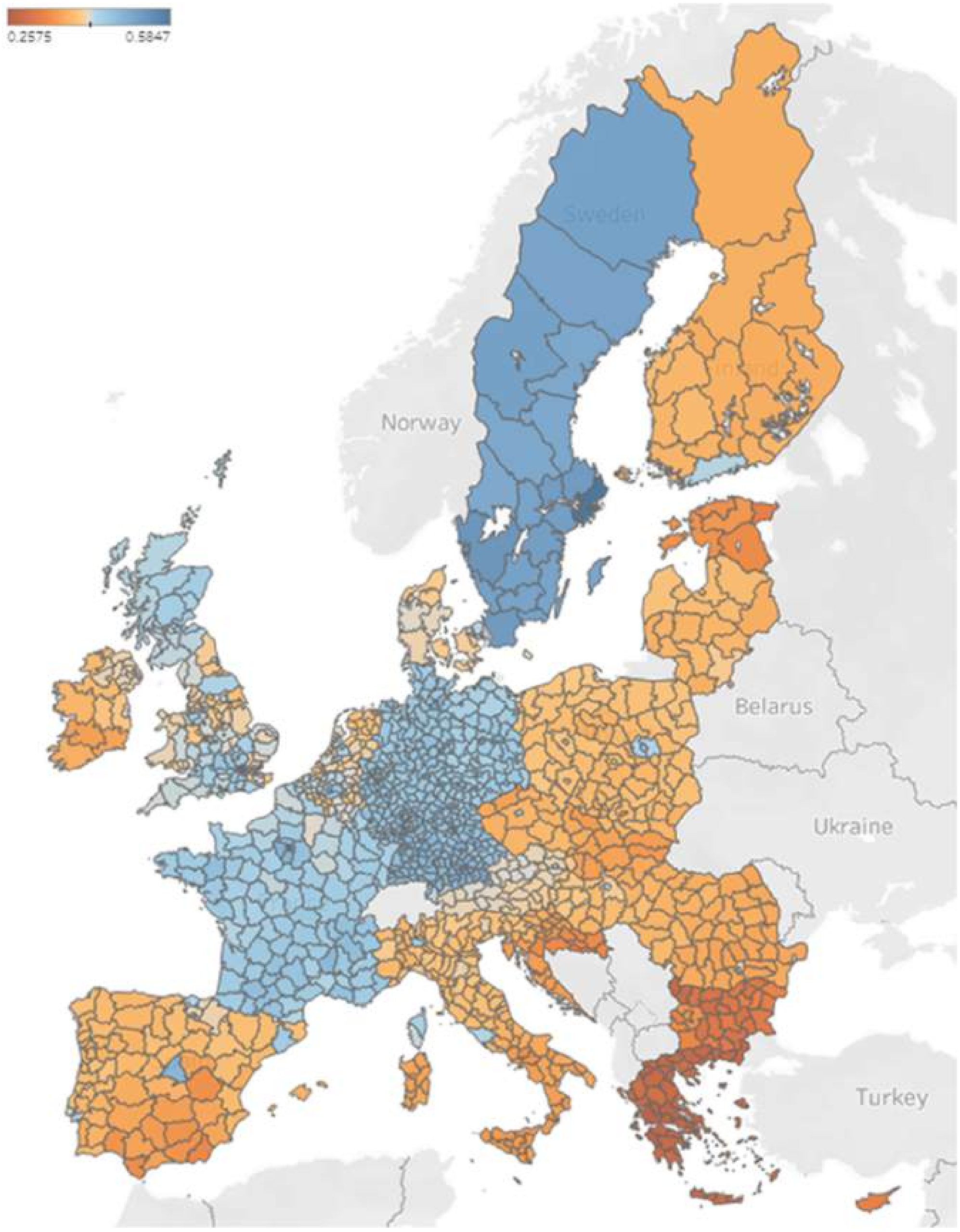

Figure 2. Final smart and sustainable performance ranking, NUTS3 cities and regions [55]).

3. Structured Literature Review and Analysis of Performance: Economic Dimensions

Our assessment of the economic strength of the European cities and regions is based on a set of three key indicators: GDP per capita, inflation rate, and unemployment. GRP, or gross regional product, is preferred where possible due to its capacity to capture the regional specificity, as reflected in Figure 1. For the majority of smaller or developing countries, GDP will still be a useful proxy.

3.1. GDP per Capita

The first indicator in our sustainability assessment for European cities and regions is GDP per capita, which is driven by a range of factors, according to Formanek (2019) [59], Bosker (2009) [60] and Österholm (2004) [61]. The positive factors include research and development (R&D) expenditure as a share of GDP, which positively stimulates innovation; foreign direct investment (FDI) inflows in relation to GDP, which trigger economic development; the share of the population aged 25–64 with tertiary education achievement, which creates the foundation for a vibrant economy; the ratio of the economically active female population, which stimulates diversity and resilience for sustainability; the number of hours worked per person per year. Negative factors include the unemployment rate, which undermines economic progress, as a higher unemployment rate is associated with a lower GDP per capita, and the inflation rate, which creates business uncertainty.

According to Table 1, based on the Environment Europe™ Sustainable Cities Database, among the top seven cities and regions in our ranking, Munich reported the lowest unemployment rate in the fourth quarter of 2019, at 3.2%, compared to as much as 10.1% in the same period for Malmö. R&D expenditures as a share of GDP were, however, the largest for Swedish cities and regions, standing at 5.5% of the country's GDP as of 2019, whereas it represented only 1.76% of the GDP in London. FDI inflows as a share of GDP were also reasonably high in Swedish cities and regions compared to other cities, except London at 3.13% in 2019, and the absolute highest in London at 141% in 2019 and 165% in 2020, illustrating the economic openness of the UK economy. London reported the largest share of the population aged 25 to 64 with a higher education attainment at 59.6% and Hamburg the lowest at 37.1%. The inflation rate was the lowest in Paris as of 2020, standing at 0.48%, and the highest was reported in the United Kingdom, at 0.989%. Stockholm, Gothenburg and Malmö reported the largest ratio of economically active female population at 90.4% in 2019, and Munich and Hamburg reported the lowest ratio at 83%. Paris and Munich both reported the largest share of the working age population relative to the rest of the population, making up 66.7% of the total population as of 2020. Stockholm reported the lowest share relatively, at 62.1%. Finally, the number of hours worked per person per year were the highest in London in 2019, at 1537 h per person per year, and the lowest was in Hamburg and Munich, at 1382 h. Following our assessment of the drivers of GDP per capita, it appears that Stockholm should display the highest amount of GDP per capita among the cities and regions assessed (see Table 1).

3.2. Unemployment Rate

The determinants of the unemployment rate rest on Edlund and Karlsson (1993) [62] as well as [63] and [64], and include the inflation rate, the change in GDP year-on-year, the index of industrial production (base 100 in 2015), the consumer price index and the real labor cost in euros. Examining the determinants in each of the top cities in detail, as can be seen in Table 2 based on the Environment Europe™ Sustainable Cities Database, the inflation rate was the lowest in Paris in 2020, standing at 0.476%, and the highest in London, at 0.989%, driving the unemployment rate upwards. Economic growth reached 1.51% in Paris in 2019, reducing the unemployment rate, whereas it reached a low of 0.55% in Hamburg and Munich that same year, causing a somewhat worse performance. However, Hamburg and Munich's index of industrial production reached 108.77 in 2019 from a base 100 in 2015, while that of Paris dropped to 92.71. The index of industrial production shows the growth of different industry groups of the economy in a certain period of time. Starting from a base of 100, an index below 100 indicates the negative growth of the industry groups of the economy. The consumer price index was the lowest in Paris in 2021, standing at 1.42%, and the highest in Munich and Hamburg, at 2.55%. Finally, the real labor cost appeared as the lowest in London, standing at EUR 24.77, compared to a high of EUR 37.5 in Paris in 2020. As the data presented in Table 1 indicate, London displayed the lowest employment among the top seven European cities and regions (see Table 2).

Table 1. Determinants of GDP per capita, NUTS3.

	Ranking	Unemployment Rate (Q4, 2019, %)	R&D Expenditure (% GDP)	FDI Inflows (% GDP)	Share of Population Aged 25–64 with Higher Education (2020)	Inflation (2020)	Ratio of Economically Active Female Population, %	Share of the Population Aged 18–64, % (2020)	Labour (Hours Worked per Person per Year)
Effect (+/−)		−	+	+	+	−	+	+	+
Stockholm	1	6.20%	5.50%	3.13%	53%	0.50%	90.38%	62.10%	1452
Paris	2	6.30%	2.19%	1.88%	51.50%	0.48%	84.87%	66.70%	1511
London	3	4.30%	1.76%	141%	59.6% (1)	0.99%	85.38%	65.20%	1537
Gothenburg	7	5.90%	5.50%	3.13%	42.30%	0.50%	90.38%	64.60%	1452
Malmö	9	10.10%	5.50%	3.13%	51.50%	0.50%	90.38%	63.50%	1452
Munich	5	3.20%	3.18%	1.75%	40.50%	0.51%	82.96%	66.70%	1382
Hamburg	19	6.40%	3.18%	1.75%	37.10%	0.51%	82.96%	65%	1382

(1): 2019; red: Worst result among the top seven; green: Best result among the top seven.

Table 2. Determinants of the unemployment rate, NUTS.

	Ranking	Inflation (2020)	Change in GDP	Index of Industrial Proction (100% in 2015)	Consumer Price Index (2021)	Real Labour Costs, € (2020)
Effect (+/−)		−	+	−	+	+
Stockholm	1	0.50%	1.26%	107.13%	1.83%	37.3
Paris	2	0.48%	1.51%	92.71%	1.42%	37.5
London	3	0.99%	1.46%	94.71%	2.10%	24.77
Gothenburg	7	0.50%	1.26%	107.13%	1.83%	37.3
Malmö	9	0.50%	1.26%	107.13%	1.83%	37.3
Munich	5	0.51%	0.55%	108.77%	2.55%	36.6
Hamburg	19	0.51%	0.55%	108.77%	2.55%	36.6

Red: Worst result among the top seven; Green: Best result among the top seven.

4. Structured Literature Review and Analysis of Performance: Smart Dimensions

4.1. Number of Patents per 1000 Inhabitants

The scale of innovation expressed in the number of registered patents (Table 3) is a major element of assessment of smart and sustainable cities, characterizing the progress in smart tech [65]. Patents, as representatives of technological innovations, drive further economic development and display the city's smartness. They are driven by a range of factors, according to the study by Jaumotte and Pain (2005) [66]. Positive determinants include the availability of scientists and engineers as a percentage of the active population, the share of population aged 25 to 64 with tertiary education achievement, the use of R&D tax incentives, the FDI share to GDP, the stock market cap to GDP, the stock of business and non-business R&D, while negative determinants include the use of FDI restrictions into the domestic market [66]. In addition, we consider the direct government spending and tax support for business R&D, the total public spending on education and the share of students in the total population.

In Stockholm, based on the Environment Europe™ Sustainable Cities Database, scientists and engineers made up as much as 15.7% of the total active population in 2020, compared to only 10.6% in Paris. Furthermore, a total of 53% of the population aged 25 to 64 had achieved a tertiary education as of 2019 in Stockholm, compared to 51.5 in Paris and 59.4% in London. Stockholm's, Gothenburg's and Malmö's share of public spending on education relative to GDP was the highest among the top 10 cities and regions, standing at 7.57% of the country's GDP in 2017. It was the lowest in Germany, at 4.9% of the country's GDP. However, the share of students in the total population was the lowest in Stockholm, standing at only 4% of the total population as of 2021, compared to 7.81% in Munich as of 2016.

Sweden, Germany, the United Kingdom and France all offer tax rebates and credits for R&D. This amounts to a 19.59% exemption of the employer's social security contributions in Sweden, or a volume-based tax credit in France. Sweden and Germany also appear as the least restrictive countries for FDI in the domestic market, compared to France and the United Kingdom, which limit or ban investments in national security-related and sensitive sectors. Accordingly, the FDI share to GDP is the largest in Sweden, standing at 3.13% in 2019, compared to as little as 0.08% in the United Kingdom. The ratio of the stock market cap to GDP is also the highest in Sweden, at 176.1% as of December 2020, compared to only 56.1% in Germany. However, German cities and regions reported the largest amount of business and non-business R&D, at EUR 72 and 33 billion, respectively, in 2018. While Swedish cities and regions reported the lowest amount in absolute values, the share of total R&D to GDP is the highest in Sweden, representing 3.34% of the country's GDP. The share is almost twice as low in the United Kingdom, standing at only 1.7% of GDP. Direct government spending and tax support for business R&D is the highest in France, representing 0.40% of the country's GDP compared to a mere 0.08% of GDP in Germany in 2018. In summary, Sweden, and most particularly Stockholm, offers the best environment in the European cities and regions for the creation of innovation patents (see Table 3).

4.2. Average Broadband Internet Speed, Mb/c

High average broadband internet speed is crucial for successful smart economy development [67] and is part of a much broader digital infrastructure necessary for the smart economy transition [68]. The key factors affecting it [69] are presented in Table 4. Broadband speed makes a contribution to digital adoption [70] and depends on a number of determinants, as studied by Lemstra, van Gorp and Voog (2014) [71]: the Gross Regional Product (GRP) per capita, the share of urban use areas and the investment in broadband per thousand people [71]. The EU's Digital Economy and Society Index [72] comprises several dimensions critical for smart economy success: human capital, connectivity, integration of digital technology and digital public services. In addition, we consider the share of broadband covered by fiber optic [73].

Table 3. Determinants of the number of patents per 1000 inhabitants.

	Ranking	Availability of Scientists and Engineers (% of Active Pop) (2020)	Share of Population Aged 25–64 with Tertiary Education (% GDP)	R&D Tax Incentives	FDI Restrictions	FDI Inflows (% GDP)	Stock Market Cap to GDP	Stock of Non-Business R&D, bln EUR (2018)	Stock of Business R&D, bln EUR (2018)	Total R&D as % of GDP (2018)	Direct Government Spending and Tax Support for Business R&D (2018)	Total Public Spending to Education (2017)	Share of Students to Total Population (2021)
Effect (+/−)		+	+	+	+	+	+	+	+	+	+	+	+
Stockholm	1	15.70%	53.00%	Yes	No	3.13%	176.10%	4.8	12.2	3.34%	0.12%	7.75%	4% (3)
Paris	2	10.60%	51.50%	Yes	Yes	1.88%	107.60%	17.9	33.9	2.20%	0.40%	5.45%	5.86% (2)
London	3	12.70%	59.60%	Yes	Yes	141.00%	102.10%	11.2	23.6	1.70%	0.33%	5.44%	4.20%
Gothenburg	7	12.10%	42.30%	Yes	No	3.13%	176.10%	4.8	12.2 (1)	3.34%	0.12%	7.57%	9.25%
Malmö	9	12.10%	51.50%	Yes	No	3.13%	176.10%	4.8	12.2	3.34%	0.12%	7.57%	6.97%
Munich	5	11.00%	40.50%	Yes	No	1.75%	56.10%	33	72	3.10%	0.08%	4.91%	7.81% (4)
Hamburg	19	10.70%	37.10%	Yes	No	1.75%	56.10%	33	72	3.10%	0.08%	4.91%	4.17%

(1) 2019; (2) 2020; (3) 2021; (4) 2016. Red: Worst result among the top seven; Green: Best result among the top seven.

Table 4. Determinants of the average broadband internet speed, Mb/c.

	Ranking	GDP per Capita, EUR	Urban Density, Persons/km^2 (Eurostat, 2019)	EU Digital Economy and Society Index (2020)	Share of Fiber by Country (OECD, 2021)	Share of Fiber by City (2021)
Effect (+/−)		+	+	+	+	+
Stockholm	1	64,700	5012	69.7	78.04%	90.00%
Paris	2	60,400	8600	52.2	45.98%	96.78%
London	3	60,400	5598	60.4	7.09%	90.00%
Gothenburg	7	44,600	1300	69.7	78.04%	96.50%
Malmö	9	39,400	2183	69.7	78.04%	96.20%
Munich	5	60,400	4767	56.1	7.11%	75.00%
Hamburg	19	59,700	2597	56.1	7.11%	72.00%

Red: Worst result among the top seven; Green: Best result among the top seven.

According to the Environment Europe™ Sustainable Cities Database, GRP per capita stood the highest in Stockholm as of 2019, at EUR 64,700, compared to EUR 39,400 in Malmö. A higher GRP per capita is normally associated with faster broadband speeds. Urban population density equally plays a role, with denser cities like Paris in theory providing faster internet speeds. Sweden's Digital Economy and Society Index is one of the highest in Europe. In summary, the highest values of broadband speed among the European municipalities were observed in Paris, Gothenburg and Malmö, as outlined in Table 4.

4.3. Creative Industry Employment

The United Nations defines creative industries as "cycles of creating, producing, and distributing goods and services that use creativity and intellectual capital as primary inputs" and underlines their importance for sustainable development (UNCTAD, 2022) [74]. The global export of creative services has increased by more than 100% between 2010 and 2020. The key components of creative service exports in 2020 included software services (39.3%); R&D (33.2%); advertising, market research and architecture (14.8%); audio-visual (8.6%); information (3.5%); and cultural, recreational and heritage services (0.5%) [74]. The widely used classification of creative industries includes such sectors as advertising, architecture, arts and crafts, design, fashion, film, video, photography, music, performing arts, publishing, electronic publishing, research and development, software, computer games, and television and radio [75].

Lazeretti, Capone and Boix (2012) [76] have studied the determinants of the creative industries' employment expressed as a percentage of creative employment in the working age population. These factors, outlined in Table 5, include the size of the city population, whether the city is a capital city and the percentage of local tertiary graduates in the population aged 25 to 64. We consider two additional determinants: the number of museums per hundred thousand inhabitants in the city and the number of films issued per year. According to the Environment Europe™ Sustainable Cities Database, London reports the largest population, with 8.9 million inhabitants, compared to only 349,000 inhabitants in Malmö. A larger population in affluent capital cities like London, Paris and Stockholm is associated with a stronger clustering of creative industry firms. Paris offers both the largest number of museums in absolute values and per hundred thousand inhabitants, with 297 museums, or 13.7 per one hundred thousand inhabitants. Malmö possesses the fewest museums, with only seven as of 2021. London, Malmö and Hamburg report only two museums per hundred thousand inhabitants, far behind Stockholm's nine museums per hundred thousand inhabitants. Finally, the United Kingdom reported the highest number of films issued in 2018 at 918, while Sweden reported the lowest at only 284. France is second to the United Kingdom, at 684 films issued in 2018. London and Paris offer the best environment for a clustering of creative industry employment, while Malmö offers the least attractive environment for such type of employment, which is reflected by the data in Table 5.

Table 5. Determinants of creative industry employment, %.

	Ranking	City Population (2021)	Capital City	Tertiary Graduates among 25–64	Number of Museums	Museums per 100,000 Inhabitants	Number of Films Released per Year (2018)
Effect (+/−)		+	+	+	+	+	+
Stockholm	1	975,277	Yes	53.00%	92	9	284
Paris	2	2,142,366	Yes	51.50%	297	13.7	684
London	3	8,908,000	Yes	59.60%	192	2	918
Gothenburg	7	583,684	No	42.30%	17	3	284
Malmö	9	348,601	No	51.50%	7	2	284
Munich	5	1,560,000	No	40.50%	42	2.85	353
Hamburg	19	1,852,478	No	37.10%	37	2	353

Red: Worst result among the top seven; Green: Best result among the top seven.

4.4. Number of Underground Stations per 1,000,000 Inhabitants

The number of underground stations per 1,000,000 inhabitants (Table 6) represents a proxy for the quality of smart infrastructure in the city and a significant factor for lowering air pollution and CO_2 emissions [77]. The study by Roy and Hugonnard (1982) [78] was one of the early examples of the determinants of the number of underground stations per 1 million inhabitants: daily traffic, profitability of the metro system and organization of the public transit system. We further consider the following indicators: the organization of the public transit system, the shape of the network, the ownership of the network and the population density.

Table 6. Determinants of the number of underground stations per 1.000.000 inhabitants.

	Ranking	Daily Traffic, mln Passengers	Investment in Upgrades, mln EUR, 2021	Number of Public Transport Modes	Number of Underground Lines	Overall Underground Length, km	Number of Stations	Ownership	Population Density
Effect (+/−)		+	+	+	+	+	+	+	+
Stockholm	1	0.97	2548	6	7	25.5	100	Private	5012
Paris	2	4.27	1600	5	16	227	303	Public	8600
London	3	3.79	1351	6	11	402	272	Public	5598
Gothenburg	7	NA	NA	4	NA	NA	NA	NA	1301
Malmö	9	NA	NA	3	NA	NA	NA	NA	2183
Munich	5	1.12	230	4	8	103	100	Public	4767
Hamburg	19	0.66	282	4	4	106	93	Public	2597

Red: Worst result among the top seven; Green: Best result among the top seven.

According to the Environment Europe™ Sustainable Cities Database, the Paris underground reported the largest daily traffic, amounting to 4.27 mln passengers, closely followed by London with 3.79 mln million daily riders, compared to only 664,000 daily riders in Hamburg. Paris's metro system is the only profitable one, reporting an operational profitability of EUR 319 million in 2019, while Hamburg's system reported EUR 68.8 million of net loss that same year. Every city offers several public transport options. The three capital cities, Paris, Stockholm and London, appear to offer the largest number of options. The Paris subway system is the densest, with 16 subway lines and 303 stations. London's system is the longest, with 402 km of tracks. Besides Stockholm's private system, all municipal subway systems are government-owned.

Paris reports the highest population density by far, at 20,965 people per km^2 based on the city of Paris' boundaries and the value of 8600 persons per km^2 if the Greater Paris boundaries are used, while that of Hamburg stood at only 2597 people per km^2 in 2019. Paris and London both, unsurprisingly, possess the largest number of underground stations per 1,000,000 inhabitants. The Paris subway system appears as the most efficient and the most likely to have its number of stations extended, displaying the quality of smart infrastructure in Paris (Table 6), while Stockholm is also observing a substantial public investment in its underground infrastructure.

5. Structured Literature Review and Analysis of Performance: Social Dimensions

The social indicators in our assessment are represented by three key components: life expectancy at birth, the share of the population aged 25–64 with a higher education and the Gini index of income inequality. These components allow us to assess the extent of the quality of life and opportunities in the European cities and regions considered.

5.1. Life Expectancy at Birth, Years

The determinants of life expectancy at birth rest on the Health at a Glance report by OECD (2017) [79]. Life expectancy is affected by a range of positive and negative factors. The positive determinants include public health expenditure per capita, percentage of tertiary graduates in the population aged 25 to 64, GRP per capita and the share of the population reporting healthy diets expressed through consuming vegetables every day. The negative determinants include the share of the smoking population, the share of the population with a daily or risky consumption of alcohol, out-of-pocket health spending, exposure to air pollution of $PM_{2.5}$ particles and the rate of unemployment [79].

According to the Environment Europe™ Sustainable Cities Database, only 7% of the population were reported to smoke in Stockholm as of 2018, compared to as much as 27.49% in Munich as of 2014, the latest data available. In 2017, only 7.1% of the Paris population aged 18 to 75 reported a daily or risky consumption of alcohol, whereas as much as 21.6% is reported in London as of 2014. Examining the healthy diets, as much as 65.3% of the United Kingdom's population reported consuming vegetables daily, in comparison with only 34.1% of Germany's population.

Out-of-pocket health spending is the lowest in France, representing only 9.25% of total health expenditure as of 2018, compared to a high of 16.71% in the United Kingdom. Exposure to air pollution by $PM_{2.5}$ particles is the highest in Paris, standing at 14.7 $\mu g/m^3$ in 2017, in contrast with Stockholm's 4.57 $\mu g/m^3$, the lowest value among the top 20 cities and regions. Public health expenditure per capita is furthermore the highest in Sweden, with EUR 5040 spent per capita in 2018, compared with EUR 3636 spent per capita in the United Kingdom. Local tertiary graduates made up 53% of Stockholm's population aged 25 to 64 and 59.6% of London's 25- to 64-years-old population in 2019.

Moreover, Stockholm's GRP per capita is the highest of the seven cities studied, standing at EUR 64,060 in 2019 compared with EUR 45,074 in Gothenburg that same year. The unemployment rate was the lowest in Munich, standing at 3.2% in the fourth quarter of 2019, compared to as much as 10.1% in Malmö that same period. The factors outlined above provide some initial background for explaining the relatively high life expectancy in Paris (84.4 years), London (84 years) and Stockholm (82.7 years) in 2014 (Table 7).

5.2. Share of Population Aged 25–64 with a Higher Education

The study by Braconier (2014) [80] provided us with the determinants of the share of the population aged 25 to 64 with tertiary education. The determinants outlined are the gross earning differentials D9/D5 (ninth decile/fifth decile of income), the gross earning differentials D5/D1, the employment ratio for individuals with a tertiary education in relation to individuals with a secondary education, the unemployment rate, the government direct expenditure per student in US dollars at Purchasing Power Parity (PPP), the share of students in tertiary private institutions, the GRP per capita and the tuition fees charged by public tertiary educational institutions to national students.

According to the Environment Europe™ Sustainable Cities Database, the gross earning differential is the lowest in Sweden, standing at 1.7 as of 2018, indicating lower income inequalities than in the United Kingdom, which had a differential standing at 2.1 in 2018. The results are similar for the D5/D1 differentials, which stand at 1.9 in Sweden and 2.1 in the United Kingdom. The employment ratio between tertiary and secondary education graduates is the highest in France, as employment is 38% higher for tertiary graduates, compared to only 3% higher for Swedish tertiary graduates. A higher employment difference between secondary and tertiary graduates influences the population to achieve tertiary education.

The unemployment rate was the lowest in Munich, standing at 3.2% in the fourth quarter of 2019, compared to as much as 10.1% in Malmö during that same period. Government direct expenditure per student was the highest in 2017 in Sweden, standing at USD 13,836 PPP, and the lowest in the United Kingdom at USD 9372 PPP. Average OECD Programme for International Student Assessment (PISA) scores of reading performances were the highest in Sweden in 2018, standing at 506, compared to only 493 that same year in France.

Furthermore, Sweden holds the lowest share of students in private tertiary institutions at only 9.7% in 2018, whereas all tertiary students in the United Kingdom studied in private institutions. Moreover, Stockholm's GRP per capita is the highest of the seven cities studied, standing at EUR 64,060 compared with EUR 45,074 in Gothenburg that same year. Finally, Sweden charges no tuition fees for education in public tertiary education to national students, compared to an average of as much as USD 12,000 PPP in the United Kingdom. Stockholm thus offers the most opportunities to its citizens to achieve higher education (Table 8).

5.3. Gini Index of Income Inequality, %

The Gini index measures the extent to which the distribution of income or, in some cases, the consumption expenditure among individuals or households within an economy deviates from a perfectly equal distribution.

We have identified the following factors influencing the Gini index of income inequality: the structure of the taxation system, the amount of income not taxed at all, the starting and maximum rate of tax, the ratio of income taxes to GDP, the membership of trade unions, the percentage of social democrats in parliament, the use of collective bargaining agreements, the average size of the retirement pension and the average size of unemployment benefits. Every city and region studied reported a progressive income taxation system.

According to the Environment Europe™ Sustainable Cities Database, in Sweden, most people earning below EUR 53,356 per year (2023) pay municipal tax at the rate of 32%, while those earning above this threshold start paying national income tax at an additional rate of 20% above this minimal income threshold. In comparison, a single German taxpayer must pay taxes from EUR 9744 of annual income. Besides Sweden's maximum rate of taxation standing at 57.2%, the maximum rate of tax in the two other countries studied stands at 45%. However, the share of income tax to GDP is the lowest in Sweden at only 42.6% of GDP in 2021, compared to 45.1% of GDP in France and 39.5% in Germany.

Trade union membership is the highest in Sweden at 65.2% as of 2019, in stark contrast with France's rate, standing at a low of 10.8% in 2016 based on the latest data available. Furthermore, in France, social democrats represent only 7.8% of the parliament's members, compared to as many as 30.9% in the United Kingdom. However, collective bargaining agreements are the most widely used in France, with a coverage of 98.5% as of 2014, compared to only 46% in Germany in 2021.

Retirement pensions are also the highest in France, with an average of EUR 1393 as of 2019, compared to only EUR 778 for a single person in Sweden. The size and distribution of the unemployment benefits differ among countries, with Sweden giving between 57% and 75% of the daily wage as a benefit as of 2020, and France giving as much as 80% of the previous salary to the unemployed worker for the first 200 days of unemployment. Following their results within the determinants of the Gini index of inequality, Stockholm, Malmö and Gothenburg are most likely to display the lowest Gini value among the European cities and regions. (Table 9).

Table 7. Determinants of life expectancy at birth, years.

	Ranking	Smoking (% Population, 2018)	Alcohol Daily or Risky Consumption (%, 2018)	Healthy Diet (% Consuming Vegetables Daily, 2014)	Private Health Spending (% Expenditure, 2018)	Exposure to Air Pollution by PM2.5 Particles, mg/m^3 (2017)	Health Expenditure per Capita, EUR (2018)	Share of Tertiary Graduates (2020)	GRP per Capita, EUR	Unemployment Rate Q4, 2019
Effect (+/−)		−	−	+	−	−	+	+	+	−
Stockholm	1	7.00%	18.30%	52.10%	13.78%	4.5	5040	53.00%	64,060	6.2%
Paris	2	22.00%	7.10%	57.60%	9.25%	14.7	3952	51.50%	94,832	6.30%
London	3	14.10%	21.60%	65.30%	16.71%	11.5	3636	59.60%	139,619	4.30%
Gothenburg	7	9.00%	16.00%	52.10%	13.78%	5.5	5040	33.60%	45,074	5.90%
Malmö	9	11.00%	16.00%	52.10%	13.78%	7.8	5040	33.75%	38,928	10.10%
Munich	5	24.87%	16.00%	34.10%	12.65%	12.8	4611	40.50%	71,348	3.20%
Hamburg	19	27.49%	16.00%	34.10%	12.65%	12.7	5472	37.10%	59,929	6.40%

Red: Worst result among the top seven; Green: Best result among the top seven.

Table 8. Determinants of the share of population aged 24–65 with a higher education.

	Ranking	Gross Earning Differentials D9/D5 (2018)	Government Direct Expenditure per Student (USD PPP) (2017)	Employment Ratio: Tertiary vs. Secondary Education (2020)	Unemployment Rate Q4, 2019	Government Direct Expenditure per Student (USD PPP) (2017)	Average PISA Score, Reading (2018)	Share of Students in Tertiary Private Institutions (2018)	GRP per Capita, EUR	University Tuition Fees, USD PPP (2017–2018)
Effect (+/−)		+	+	−	−	+	+	−	+	−
Stockholm	1	1.7	13,836	103.00%	6.2%	13,836	506	9.70%	64,060	0
Paris	2	1.8	10,495	138.00%	6.30%	10,495	493	23.70%	94,832	330
London	3	2.1	9372	118.50%	4.30%	9372	504	100.00%	139,619	12,000
Gothenburg	7	1.7	13,836	113.30%	5.90%	13,836	506	9.70%	45,074	0
Malmö	9	1.7	13,836	113.30%	10.10%	13,836	506	9.70%	38,928	0
Munich	5	1.8	11,628	131.60%	3.20%	11,628	498	10.50%	71,348	133
Hamburg	19	1.8	11,628	131.60%	6.40%	11,628	498	10.50%	59,929	133

Red: Worst result among the top seven; Green: Best result among the top seven.

Table 9. Determinants of Gini index of income inequality, %.

	Ranking	Structure of Taxation System (Income)	Income Not Taxed, EUR (2021)	Tax Rate Range, % (2021)	Highest Tax Rate, % (2020)	Share of Income & Property Taxes in GDP, %	Membership of Trade Unions	Share of Social Democrats in Parliament	Collective Bargaining Agreements, OECD (2018)
Effect (+/−)		−	−	−	−	−	−	−	−
Stockholm	1	Progressive	0	32–52%	57.10%	42.60%	65.20%	28.70%	88.00%
Paris	2	Progressive	10,083	10–45%	45.00%	45.10%	10.80%	7.80%	98.00%
London	3	Progressive	14,694	20–45%	45.00%	35.30%	23.50%	31.07%	26.00%
Gothenburg	7	Progressive	0	32–52%	57.10%	42.60%	65.20%	28.70%	88.00%
Malmö	9	Progressive	0	32–52%	57.10%	42.60%	65.20%	28.70%	88.00%
Munich	5	Progressive	9744	14–45%	45.00%	39.50%	16.30%	27.98%	54.00%
Hamburg	19	Progressive	9744	14–45%	45.00%	39.50%	16.30%	27.98%	54.00%

Red: Worst result among the top seven; Green: Best result among the top seven.

6. Structured Literature Review and Analysis of Performance: Environmental Dimensions

The environmental indicators in our assessment framework are represented by six key components: annual per capita CO_2 emissions, the percentage of renewables in the energy mix, PM_{10} average annual concentrations, the amount of municipal waste in kg per person per year, the domestic water consumption in m^3 per person per year and the municipal recycling rate [81]. These indicators allow us to perform an assessment of the environmental sustainability of the European cities and regions.

6.1. Annual per Capita CO_2 Emissions

The determinants of the CO_2 emissions per person per year [82] (Table 10) are based on seven elements explored in our previous research: the shares of coal and renewables in the energy mix [83], the daily mean temperature, the presence and amount of a carbon tax, the recycling rate, the journey modal split and a city's OECD capital status [77].

Table 10. Determinants of annual average CO_2 emissions.

	Ranking	OECD Capital Status	Daily mean Temperature, Deg C (2020)	Share of Coal, % (2019)	Share of Renewables (2019)	Share of Trips Made by Walking Cycling and Public Transport	Recycling Rate (2020)	CO_2 Tax, EUR (2021)
Effect (+/−)		−	−	+	−	−	+	−
Stockholm	1	Yes	10 °C	3.00%	71.00%	54.00%	30.00%	114.0
Paris	2	Yes	14.3 °C	2.20%	37.30%	73.00%	20.70%	44.6
London	3	Yes	13.6 °C	3.21%	11.10%	61.00%	33.40%	18.0
Gothenburg	7	No	10.25 °C	0.23%	52.25%	46.30%	34.00%	114.0
Malmö	9	No	10.75 °C	0.41%	50.31%	65.00%	37.00%	114.0
Munich	5	No	11.25 °C	2.60%	19.70%	54.50%	54.50%	25.0
Hamburg	19	No	11.25 °C	52.20%	4.70%	58.00%	58.00%	25.0

Red: Worst result among the top seven; Green: Best result among the top seven.

According to the Environment Europe™ Sustainable Cities Database, taking all the factor values into consideration, Stockholm and Paris display the best results among all of the European cities and regions. While Gothenburg uses coal for only 0.23% of its energy consumption, this amount rises to 52.2% for the city of Hamburg. Paris and Stockholm both used coal for less than three percent of their energy consumption as of 2019. Stockholm reported the largest share of renewable energies in the energy mix of the different cities in 2019: 71% of its energy was provided by renewables, compared with only 4.7% for Hamburg.

Sweden has also implemented a nation-wide carbon tax, priced at EUR 114 a ton, followed by France with a price of EUR 44.6 a ton. The United Kingdom has yet to implement a carbon tax. German cities report the highest recycling rate of the top 10 cities with a rate as high as 58% for Germany, compared with a mere 20.7% for the city of Paris, which increases CO_2 emissions due to the fact that German cities use a large share of coal in their energy mix. Swedish cities report a recycling rate between 30 and 37%, as most of the waste is sent to incineration for heating purposes. As for the journey modal share, however, Paris reported the largest share of trips conducted by cycling, public transport and walking in 2019, amounting to 75% of the total of trips. Stockholm, Munich and Hamburg reported car use shares of up to 46%.

Paris reported the highest temperature out of the top 10 cities studied with an average of 14.3 °C over the year 2020, while Stockholm reported the lowest with an average of 10 °C. Finally, an OECD capital city status has been demonstrated by the authors to be a determinant of lower CO_2 emissions per capita due to the fact that in these cities large OECD research programs on reducing traffic congestion and pedestrianization have been carried since the 1970s. The C40 club of cities includes many OECD capitals on their board, and it is important to mention that Stockholm, Gothenburg and Malmö were among the first European cities to have pedestrianized their city center areas. Following our assessment of the determinants of CO_2 emissions per person per year, we expect Stockholm and Paris to display the lowest levels of CO_2 emissions (Table 10).

6.2. Percentage of Renewable Energy in the Energy Mix

The percentage of renewable energy in the energy mix (Table 11) is assessed using the research by Mac Domhnaill and Ryan (2020) [84], citing twelve elements as determinants: petrol and gas prices, the energy tax per liter of fuel, energy interconnection, the growth of the tax and levy components of electricity prices, solar and wind power potentials, GRP per capita, hydropower share, fossil fuel share and the nuclear share in the energy mix. We have added another determinant: the share of taxes and levies in the electricity prices. Swedish cities reported the highest amount of renewable energy use in their energy mix.

According to the Environment Europe^{TM} Sustainable Cities Database, the petrol price was highest in Sweden as of July 2021, with a price of EUR 1.61 per liter, and lowest in Germany at EUR 1.49. The gas price also stood at its highest in Sweden as of late 2019 with EUR 0.117 per kwh, compared with a low of EUR 0.05 per kwh in the United Kingdom. As of 2020, France reported the highest energy tax per liter of fuel, with a rate of EUR 0.68 per liter, compared to a low of 0.62 per liter for Sweden. However, Sweden reported the highest amount of growth of the tax and levy components of the country's electricity prices, with a growth rate of 200% between 2019 and 2020, compared with a decreasing rate of 17.8% in the United Kingdom. Sweden's share of taxes and levies in the country's electricity prices amounted to 38.2% as of 2020, 8 points higher than the United Kingdom's share at 30.5% but still 15 percentage points below Germany's share, standing at 53%.

Regarding the electricity grid interconnection, Germany's interconnection is the largest of the three countries studied, standing at 9709 ktoe in 2019. A larger interconnection is associated by the authors with a better ability to make use of renewable energy in a country's energy mix. At the opposite end, the United Kingdom recorded the lowest interconnection at only 2401 ktoe in 2019 and the largest amount of energy it imports in comparison to its exports, as it imports 7.3 times more energy than it exports. In terms of solar power potential, Paris benefits from the largest potential, while Stockholm faces the lowest. As for wind potential, Gothenburg profits from the largest potential per year and London the lowest.

Mac Domhnaill and Ryan have analyzed GRP per capita as having a positive effect on the use of renewable energy in the energy mix. Stockholm reports the highest GRP per capita out of the seven cities, with an amount of EUR 64,700, in comparison with Malmö's GRP per capita of only EUR 39,400. Stockholm's energy mix was composed of 53% hydropower in 2018, while Hamburg did not use any hydropower in its mix as of 2019. Gothenburg had the lowest share of fossil fuels in its energy mix as of 2018, standing at only 0.97%. In comparison, Munich's share stood at 88.1% that same year. However, Munich was the only city of the seven studied to not use any nuclear energy in its energy mix, compared to Paris, which uses it at a share as high as 71.7%. A higher share of nuclear energy is associated with a lower incentive to develop the use of renewable energies. The share of taxes and levies in the electricity prices was the highest in Germany in the first semester of 2020, representing 53% of the final price. By contrast, it represented only 30.46% of the final price in the United Kingdom. The Swedish cities of Gothenburg, Malmö and Stockholm clearly show the largest commitment to the development of renewable energy in their energy mix and should display the largest percentage of renewable energy use (Table 11).

6.3. *PM_{10} Average Annual Concentrations, mg/m^3*

Research by Karagulian et al. (2015) [85] has provided us with the proxy determinants of PM_{10} average annual concentrations (Table 12): CO_2 emissions from traffic, the share of coal and gas in the energy mix and CO_2 emissions from domestic fuel burning. The other determinants included in our analysis are as follows: the number of cars per thousand inhabitants, the population size [86], the green space per capita, the average temperature, the % of electric cars in circulation, the number of underground stations and the journey modal share [87–89]. Considering CO_2 emissions as a proxy, according to the Environment Europe™ Sustainable Cities Database, 7.9 million tons of CO_2 emissions are produced by London's traffic in a single year, followed by Paris' 4.2 million tons recorded in 2018, far above Malmo's 267,000 tons produced in the same year. As for coal, Gothenburg reports the lowest share of gas in the city's energy mix, with only 0.55%, compared to as much as 39.5% for London as of 2018. CO_2 emissions from domestic fuel burning were the lowest in Sweden as of 2019, with only 0.58 million tons, and the highest in Germany, with 89.76 million tons produced in 2019. London boasted as of 2018 the lowest number of cars per thousand inhabitants, with only 295 cars, compared to 586 cars per thousand inhabitants in Munich. However, London faces the largest population size out of the seven cities, leading to a higher concentration of PM10 pollution in the city. Malmö benefits from the largest amount of green space per capita, with 46.4 m^2 as of 2019, while Paris suffers from only 14.5 m^2 per capita. Sweden reports the highest percentage of electric cars in the country, with electric cars representing 3.74% of all cars in circulation, while Germany's electric cars represent only 1.23% of all cars in circulation as of 2020. Paris benefits from the highest number of underground stations out of the seven cities studied, with 303 stations compared to only 47 in Hamburg. Stockholm inhabitants use a private car for as much as 46% of their trips, the highest amount of all cities studied. In comparison, Paris inhabitants use a car for only 25% of their trips and use other transport modes, such as walking or using public transport, for 75% of them. Following our analysis of the determinants of PM_{10} average annual concentrations, Gothenburg and Malmö should display the lowest concentrations of PM_{10} particles (Table 12).

Table 11. Determinants of the share of renewable energy in the energy mix.

	Ranking	Petrol Price, Euro (2021)	Household Gas Price, EUR per kWh (2020)	Energy Tax per l of Fuel, EUR (2020)	Energy Imports, kt	Energy Exports, kt	Population Growth, % (2019)	Growth of Tax and Levy Component of Electricty Prices (2019 to 2020), %	Solar Power Potential (kWh/year, 2010)	Wind Power Potential (m/s*km^2/year, 2010)	GRP per Capita, EUR	Hydro Share (2018)	Fossil Fuel Share (2018)	Nuclear Share (2018)	Share of Taxes and Levies in Electricity Prices (2020)
Effect (+/−)		+	+	+	−	+	+	+	+	+	+	+	−	−	+
Stockholm	1	1.613	0.1167	0.620	780	3029	14.00%	200%	676.1–845.0	204.547–487.852	64,060	53.00%	5%	21%	38.20%
Paris	2	1.540	0.084	0.680	1341	6307	3.10%	12.80%	951.1–1113.1	79.181–204.546	94,832	12.40%	7%	71.70%	34.40%
London	3	1.552	0.050	0.650	2111	291	1.16%	−17.80%	845.1–951.0	0–79.180	139,619	1.70%	47.50%	19.50%	30.46%
Gothenburg	7	1.613	0.1167	0.620	780	3029	10.00%	200%	951.1–1113.1	487.853–1031.076	45,074	38.94%	0.97%	40.94%	38.20%
Malmö	9	1.613	0.1167	0.620	780	3029	10.20%	200%	676.1–845.0	204.547–487.852	38,928	22.12%	23.59%	21.70%	38.20%
Munich	5	1.490	0.059	0.650	3450	6529	3.30%	36.60%	951.1–1113.1	79.181–204.546	71,348	1.00%	88.10%	0.00%	53.01%
Hamburg	19	1.490	0.059	0.650	3450	6529	3.10%	36.60%	676.1–845.0	0–79.180	59,929	0.00%	63.10%	12.30%	53.01%

Red: Worst result among the top seven; Green: Best result among the top seven.

Table 12. Determinants of PM_{10} average annual concentrations, µg/m^3.

	Ranking	CO_2 Emissions from Traffic, mln t (2018)	Share of Coal, % (2019)	Share of Gas (2018)	CO_2 Emissions from Domestic Fuel Burning, mln t (2019)	Cars per 1000 Inhabitants	Population (2021)	Green Space per Capita, m^2 (2019)	Daily Mean Temperature, Deg C (2020)	Electric Cars (%, 2020)	Number of Underground Stations per mln Inhabitants (2021)	Journey Modal Share, Cars (2019)	Share of Trips Made by Walking Cycling and Public Transport
Effect (+/−)		+	+	+	+	+	+	−	+	−	−	+	−
Stockholm	1	1.019	3.00%	2.00%	0.582	394	975,277	41.61	10 °C	3.74%	102	46.00%	54.00%
Paris	2	4.200	20.20%	5.70%	41.26	420	2,142,366	14.50	14.3 °C	1.39%	128	27.00%	73.00%
London	3	7.929	3.21%	39.50%	67.64	295	8,908,000	19.23	13.6 °C	1.38%	30	39.00%	61.00%
Gothenburg	7	0.511	0.23%	0.55%	0.682	469	583,684	45.26	10.25 °C	3.74%	NA	53.70%	46.30%
Malmö	9	0.267	0.41%	23.04%	0.582	479	348,601	46.37	10.75 °C	3.74%	NA	35.00%	65.00%
Munich	5	ND	2.60%	22.90%	89.76	586	1,560,000	21.98	11.25 °C	1.23%	102	45.50%	54.50%
Hamburg	19	ND	52.20%	24.30%	89.76	430	1,852,478	30.15	11.25 °C	1.23%	25.00	42.00%	58.00%

Red: Worst result among the top seven; Green: Best result among the top seven.

6.4. Municipal Solid Waste, in kg per Person per Year

We draw the determinants of municipal solid waste per person per year from the research of Romano, Rapposelli and Marucci (2019) [90]: population density, the median age of inhabitants, the ownership of the waste utility company and the adoption of a zero-waste strategy (Table 13). According to the Environment Europe™ Sustainable Cities Database, Paris benefits here from the highest population density, with 20,965 people per km^2, as Romano et al. found that the separate collection rate is higher when the population density is higher. Gothenburg fares the worst with this determinant, with a density of only 1301 people per km^2 as of 2020. An older median age of the city's inhabitants is associated with a lower production of municipal solid waste. Munich's inhabitants' median age was the highest at 41.6 years old in 2020, compared to London's inhabitants' median age of only 35.6 years old as of 2019. Almost every city studied here is covered by a public waste utility company, except for Munich, which uses a dual system mixing public and private companies. However, Paris and Gothenburg both use private subcontractors for waste collection. Every city except Gothenburg and Malmö have adopted a zero-waste strategy as of 2021. In Paris, municipal solid waste generated was estimated at 371 kg per person per year in 2019. That figure stands at 392 kg in London. In Sweden, municipal waste generation per capita stands at 467 kg per person. Finally, in Germany the amount of municipal waste generated per person stands at 457 kg per year as of 2019. Paris appears to display the lowest municipal solid waste generation per person among the European cities and regions studied (Table 13).

Table 13. Determinants of the annual municipal solid waste generation, kg per person per year.

	Ranking	Urban Density, persons/km^2 (Eurostat, 2019)	Median Age of Inhabitants (2020)	Ownership of the Waste Utility (2021)	Zero Waste Strategy	GRP per Capita, EUR	Tourist Visits (2018)	Tourist Visits (2021)
Effect (+/−)		+	+	+	+	+	+	+
Stockholm	1	5012	39.4	Public	Yes	64,060	2,604,600	5,420,000
Paris	2	8600	38	Public	Yes	94,832	17,560,200	22,600,000
London	3	5598	35.6	Public	Yes	139,619	19,233,000	2,600,000
Gothenburg	7	1301	39.1	Private	No	45,074	5,250,000	3,880,000
Malmö	9	2183	38.5	Public	No	38,928	1,970,000	1,320,000
Munich	5	4767	41.6	Public & Private	Yes	71,348	4,066,600	3,110,000
Hamburg	19	2597	41	Public	Yes	59,929	7,600,000	3,300,000

Red: Worst result among the top seven; Green: Best result among the top seven.

6.5. Domestic Water Consumption, m^3 per Person per Year

The study of the amount of domestic water consumption per person per year uses determinants based on the research by Romano, Salvati and Guerrini (2015) [91]: altitude, the annual expenditure for residential household use of 192 cubic meters of water, the ownership of the water utility and the size of the city population (Table 14). We added GRP per capita as a determinant, as a higher GRP per capita is associated with a higher water consumption level. A higher altitude has been associated by Romano et al. with a lower water consumption level. According to the Environment Europe™ Sustainable Cities Database, while Munich stands at a height of 526 m above sea level, Malmö is only sitting 12 m above sea level. The cost of 192 cubic meters of water is the highest in the city of Hamburg, at EUR 768 in 2021, and the lowest in Munich, at only EUR 341. A higher cost of water is associated with a lower consumption of water. According to Romano et. al, publicly owned water utilities are associated with lower costs, leading to increased consumption of water. Except for London, for which water supply is operated by four private companies, every other city studied is supplied by a wholly publicly owned utility. The authors also found that a larger city population is associated with a higher amount of water consumption per person and per year. Greater London, with a population of

8.9 million inhabitants, has the largest population of the seven cities studied, and Malmö has the lowest, with only 38,600 inhabitants. Finally, Stockholm reports the largest GRP of all the cities studied at EUR 64,700 in 2019, compared with only EUR 39,400 in Malmö that same year. Malmö offers the best opportunities for a lower per capita out of the European cities and regions studied. In Sweden in 2016, water consumption per household per day amounted to 148 liters in Stockholm, 163 liters in Malmö and 153 liters in Gothenburg. It reached 187 liters in Paris and 149 liters in London. In Germany, water consumption per household per day amounted 123 liters in 2016 (Table 14).

Table 14. Determinants of domestic water consumption, m3 per person per year.

	Ranking	Population (2021)	GRP per Capita, EUR	Altiude Above Sea Level, m	Annual Expenditure on Residential Household Use of 192 m^3 of Water (2017)	Utility Ownership	Tourist Visits (2018)	Tourist Visits (2021)
Effect (+/−)		+	+	−	−	+	+	+
Stockholm	1	975,277	64,060	19	588.22	Public	2,604,600	5,420,000
Paris	2	2,142,366	94,832	33	702.35	Public	17,560,200	22,600,000
London	3	8,908,000	139,619	77	623.54	Private	19,233,000	2,600,000
Gothenburg	7	583,684	45,074	49	664.69	Public	5,250,000	3,880,000
Malmö	9	348,601	38,928	12	657.13	Public	1,970,000	1,320,000
Munich	5	1,560,000	71,348	526	340.99	Public	4,066,600	3,110,000
Hamburg	19	1,852,478	59,929	25	768.00	Public	7,600,000	3,300,000

Red: Worst result among the top seven; Green: Best result among the top seven.

6.6. Recycling Rate

We used the study by Sidique, Joshi and Lupi (2010) [92] to assess the determinants of the recycling rate (Table 15): the presence of a landfill tax and of a mandatory recycling ordinance, the percentage of the population that has access to curbside recycling, the GRP per capita and the population density, with all of the variables having a positive impact on the recycling rate. We consider the following additional determinants: the percentage of tertiary education attainment among 25- to 64-year-olds; the real rate of processing of waste; for determinants with a negative impact, the amount of waste being sent abroad (in total and excluding the OECD member countries); and the measures in support of or opposing incineration.

According to the Environment Europe™ Sustainable Cities Database, France reports the highest landfill tax to date, reaching up to EUR 152 per ton for non-authorized landfills, in conjunction with bans on untreated waste and on separated waste already collected for recycling. Germany does not possess a landfill tax, only a landfill ban since 2005 on all untreated waste with a Total Organic Carbon (TOC) above three percent. All cities but London have implemented a form of mandatory recycling ordinance. It is the most comprehensive in Stockholm, with a mandatory sorting and recycling ordinance for both businesses and households. Paris has made recycling mandatory only for public and private businesses of over 20 employees as of 2019. All cities offer their entire population access to curbside recycling via the provision of sorting bins.

A higher GRP per capita is associated with a higher rate of recycling. Stockholm reports the highest GRP per capita out of the seven cities, with an amount of EUR 64,700, in comparison with Malmo's GRP per capita of only EUR 39,400. According to the authors, a higher population density makes the provision of recycling services cheaper, leading them to be more developed. Paris reports the highest population density, with 20,965 people per km^2, in comparison with only 1301 people per km^2 in Gothenburg. Stockholm's rate of 25- to 64-year-old inhabitants who attained tertiary education is the highest of the cities studied, standing at 53%. It was as low as 25.4% in London in 2019. Stockholm also reports the highest real rate of waste processing, with as much as 99.3% of waste processed and only 0.7% sent to the landfill in 2018.

Table 15. Determinants of municipal solid waste recycling rate, %.

	Ranking	Urban Density, persons/km2 (Eurostat, 2019)	GRP per Capita, EUR	Share of Tertiary Graduates (2020)	Mandatory Recycling Ordinance	Share of Population with Access to Kerbside Recycling	Real Rate of Waste Processing (2018)	Waste Sent Abroad, t (2018)	Waste Sent Abroad to Non-OECD Countries (2018)	Support for Incineration	Tourist Visits (2018)	Tourist Visits (2021)
Effect (+/−)		+	+	+	−	+	+	−	−	−	−	−
Stockholm	1	5012	64,060	53.00%	Mandatory	100%	99.30%	384,942	886	Supported	2,604,600	5,420,000
Paris	2	8600	94,832	51.50%	Mandatory	100%	95.70%	2,179,659	102,324	Zero waste strategy	17,560,200	22,600,000
London	3	5598	139,619	59.60%	Not mandatory	100%	80.00%	4,778,419	623,535	Strong opposition	19,233,000	2,600,000
Gothenburg	7	1301	45,074	33.60%	Mandatory	100%	99.30%	384,942	886	Supported	5,250,000	3,880,000
Malmö	9	2183	38,928	33.75%	Mandatory	100%	99.30%	384,942	886	Supported	1,970,000	1,320,000
Munich	5	4767	71,348	40.50%	Mandatory	100%	69.44%	4,034,167	13,222	Limited	4,066,600	3,110,000
Hamburg	19	2597	59,929	37.10%	Mandatory	100%	69.44%	4,034,167	13,222	Waste avoidance encouraged	7,600,000	3,300,000

Red: Worst result among the top seven; Green: Best result among the top seven.

Furthermore, Sweden sends the least of its waste abroad out of the three countries studied, with only 385,000 tons of waste sent abroad and only 896 tons sent to non-OECD member countries in 2018, and with 0.23% of the total waste sent abroad. In contrast, the United Kingdom sent as much as 4.8 million tons of waste abroad in 2018, of which 624,000 were sent to non-OECD member countries; 13% of all waste was sent abroad. Swedish cities, however, suffer from a strong support for incineration, stemming from its use for district heating in the country. This goes in opposition to the rest of the cities studied, such as London, whose mayor expressed a strong opposition to building any more incineration plants, or Paris, whose zero-waste strategy aims at ending the incineration of waste that cannot be recycled.

Out of the 10 determinants of the municipal recycling rate studied, Stockholm obtained the best results in 7 of them. Despite displaying the best results in the determinants of the recycling rate, Stockholm reports a recycling rate of only 30%. This is due to Sweden's cities' policy of district heating, leading to waste management in the form of waste incineration. Gothenburg and Malmö have recycling rates of 34 and 37%, respectively. Munich and Hamburg reported the highest recycling rate, at 54.4 and 58%, respectively, in 2018 and 2019. London reported a recycling rate of 33.4% in 2019, while Paris reported the lowest rate at just 20.7% in 2019 (Table 15).

7. Empirical Application

To illustrate how the approach outlined on the previous pages could be put in practice, we would like to present one of the constituent models of the Urban Galaxy in the Environment Europe^{TM} Universe Model. It deals with per capita CO_2 emissions, representing the environmental dimension in the sustainable cities assessment methodology presented in Figure 1. Based on empirical data sourced from 71 different cities around the world, we were able to construct an econometric model of urban per capita CO_2 emissions. The model connects this important indicator with four groups of factors (Figure 3).

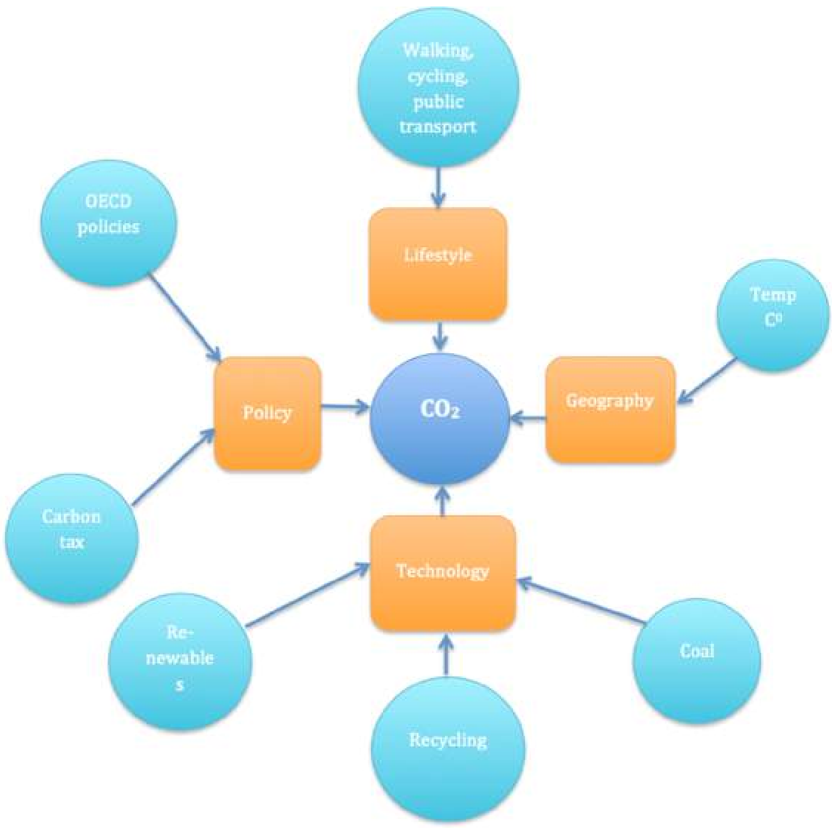

Figure 3. Urban CO_2 model.

The factors outlined in Figure 3 include Geography, Technology, Policy and Lifestyle. Geography is represented by the average annual air temperatures, and Technology deals with the share of coal, share of renewables and recycling rates. Policy variables include OECD policies and carbon taxes. The Lifestyle dimension is represented by the share of trips made by walking, cycling and using public transport in a given city. Figure 4 illustrates the fit between the actual data in red and the modeled data in blue. The specific statistical coefficients in the model are presented in Table 16. The R^2 amounts to 0.805394, which illustrates that this model explains four-fifths of the variance in the per capita urban CO_2 emissions, which is rather good. Most of the variables chosen are statistically significant at one percent, with only one of them significant at five percent.

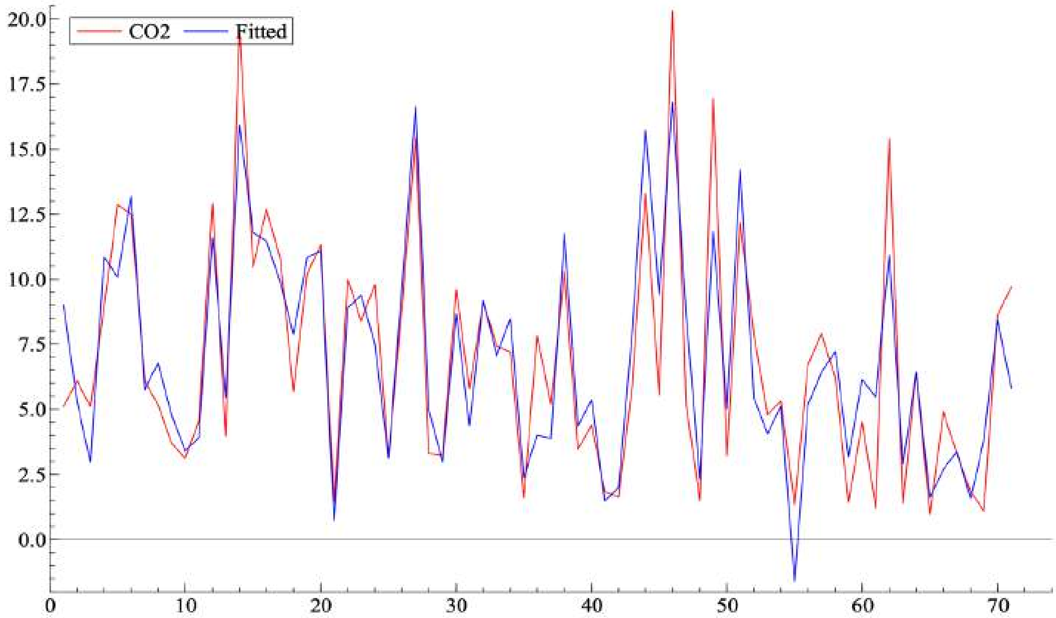

Figure 4. Urban CO_2 econometric model. *Y*-axis represents per capita CO_2 emissions in different cities; the *X*-axis represents various global cities in the sample.

Table 16. Coefficients in the urban CO_2 econometric model.

Variable	Coefficient	Std.Error	t-Value	t-Prob	Part.R^2
Constant	15.2640	1.023	14.9	0.0000	0.7794
Daily Mean Temperature	−0.234784	0.04427	−5.30	0.0000	0.3087
OECD Capital Status	−2.29855	0.6474	−3.55	0.0007	0.1667
Share of Renewables in the Energy Mix	−0.0376761	0.01115	−3.38	0.0013	0.1534
Share of Coal in the Energy Mix	0.0486420	0.009920	4.90	0.0000	0.2762
Share of Trips made by Walking, Cycling and Public Transport	−0.113082	0.01036	−10.9	0.0000	0.6543
Recycling Rate	0.0692216	0.01286	5.38	0.0000	0.3150
CO_2 Tax	−0.0306765	0.01428	−2.15	0.0355	0.0683

Red colour denotes all the coefficients statistically significant at levels stronger than 5%. Source: Environment Europe Cities Database, 71 observations, R^2 = 0.805394.

If we try to interpret the coefficients in the model, we come to the following conclusions. Under a hypothetical ‘do nothing’ scenario, the average per capita urban CO_2 emissions in cities around the world would have been equal to 15 tons per person per year. Warmer climates tend to lead to less CO_2 generated on a per capita basis due to lower energy consumption for heating in winter. OECD capital cities tend to generate 2 t CO_2 fewer emissions per capita than other cities. This could be attributed to the pioneering role of OECD capital cities like Paris, which hosts the OECD headquarters, in stimulating public transport and pedestrianization, to the early research conducted by the OECD on reducing traffic congestion, to the fact that a prominent C40 group is largely driven by OECD capitals or to other, most likely technological, factors. More coal in the energy mix tends to result in higher per capita CO_2 emissions, and more renewables result in less CO_2 emitted per year. Higher recycling rates tend to result in higher per capita CO_2 emissions, due to the fact that energy mixes around the world are not yet completely renewable or zero carbon and recycling requires energy input. One could argue that dealing with built obsolescence and extending product lifetime could have better environmental impacts than increasing the rate at which obsolete devices that people tend to upgrade every year get recycled again and again. CO_2 taxes have been shown to be beneficial for reducing per capita CO_2 emissions; however, they cannot be seen as a panacea because they should be used in conjunction with multiple other tools and approaches, including promoting public transport and making sure that cities are walkable. This model illustrates the approach we have taken to examine the determinants of smart and sustainable performance KPIs that will be immensely valuable for city mayors and urban sustainability decision-makers around the world because they provide tangible empirical evidence for the success or failure of specific policies and make the results robust due to the fact that the data come from multiple points around the world.

8. Discussion

The present study makes but a first step in a large project establishing solid models explaining urban smart and sustainable performance. The factor tables based on the literature review and the available data presented for each of the constituent KPIs in this paper are, therefore, the necessary foundation for all subsequent modeling work. It should be noted that additional explanatory factors could emerge through detailed econometric analysis of each dimension. In addition, one should be made aware that oftentimes the precise methodologies for calculating CO_2 emissions or measuring any other aspect of urban smart and sustainable performance could vary among cities and regions, especially in the context of the developing world. Despite this fact, it was possible to build a solid statistical model with a good capacity to explain. The methodological discrepancies, we could say, were taken care of by the residuals in the model. As far as other KPIs are concerned, including PM_{10} pollution, only detailed empirical modeling could provide a solid basis for policy advice. This is why continuing our project is of paramount importance, paying particular attention to the interaction and mutual influence of the urban smart and sustainable policies in place.

9. Conclusions

Based on the sustainability ranking of over 1300 NUTS3 cities and regions in Europe explored in Shmelev and Shmeleva (2023) [55], in this paper we offered a detailed discussion of the possible reasons of why the cities rank higher or lower. Using a powerful and policy-relevant set of 17 indicators, and focusing on MCDA at the NUTS3 level, cities and regions were ranked based on social, economic, environmental and smart performance.

Among the seven cities that we shortlisted for this detailed assessment, we found that Stockholm, Paris and London are the best-performing municipalities under economic policy priorities, while Swedish cities ranked very high based on smart performance, followed by London and Paris. Considering the indicators of social performance, Stockholm clearly leads the ranking. The city is followed by its Swedish counterparts, while Munich and Hamburg continue to somewhat lag behind. These rankings are consistent with those for the environmental indicators, in which Swedish cities occupy the first spots. Paris is ranked just below these cities.

In this paper, we went one step further and explored the detailed analysis of contributing factors determining urban sustainability performance in the leading cities. The results clearly show that there is a strong potential to employ detailed models similar to the Environment Europe^{TM} Universe Model used in Shmeleva and Shmelev (2019) [77] for detailed policy recommendations on how to make cities more sustainable. The detailed analysis in this paper clearly demonstrated how the performance of Stockholm and other Swedish cities rests on very strong fundamentals in economic, smart, social and environmental performance.

Our assessment thus allows one to understand the key factors and policies implemented by the leading municipalities and offers insights on the necessary steps to improve one municipality's ranking.

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