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RESEARCH ARTICLE

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Global urban sustainability assessment: A multidimensional approach

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Abstract

A new strategic direction for greening our cities and making them smart to reduce the environmental impact of their performance, increase employment and economic viability, and to enhance the quality of life requires a thorough assessment of sustainability and smart urban performance. This paper considers a database of over 90 global cities including London, New York, Hong Kong, San Francisco, Los Angeles, Sao Paolo, Rio de Janeiro, Buenos Aires, Paris, Berlin, Stockholm, Moscow, Beijing, Seoul, Singapore, Shanghai, Sydney and Tokyo exploring linkages between different sustainability and smart city dimensions. To assess urban sustainability performance, this study applied a multi-criteria approach using a panel of 20 indicators to a set of 57 global cities. The assessment comprised important aspects of energy transitions, focusing on the drivers of CO_2 emissions in cities, including the share of coal in the energy mix, public transport and cycling patterns, waste recycling, the water-energy nexus, as well as the role of smart and creative economy. The results show that San Francisco leads in economic and environmental priorities, and Stockholm leads in social and smart city priorities. Seoul consistently performs very successfully across the whole spectrum of indicators. We devote considerable attention to the strategies, policies and performance of the leading cities, namely, San Francisco, Stockholm and Seoul. This assessment could be a valuable tool for policy-makers and investors, and could help identify linkages between different sustainability dimensions, as well as investment opportunities in cities with sustainability potential.

KEYWORDS

environmental policy, indicators, multi-criteria decision aid, smart city, sustainable cities, sustainable development

1 | INTRODUCTION

The UNEP Green Economy Report highlighted urban sustainability as one of its important dimensions (UNEP, 2011). This interdisciplinary topic (Shmelev & Shmeleva, 2012) has received a lot of attention in the EU, the USA, and increasingly China and Latin America, ever since the Rio Summit of 1992, the Rio + 20 Summit in 2012 and, in particular, in light of the recent HABITAT III forum held in Quito, Ecuador, in 2016. The new UN Habitat World Cities Report firmly links the New Urban Agenda with Sustainable Development Goals (SDG) (UN HABITAT, 2016): the 11 SDG for “Sustainable Cities and Communities” aim to “make cites and human settlements inclusive, safe, resilient and sustainable” (UN, 2015b). UNECE and ITU launched a new United for Smart and Sustainable Cities initiative in 2016.

Urban sustainability is defined as the multidimensional capacity of a city to simultaneously operate successfully in economic, social and environmental domains. Sustainable urban policy developments have been explored by Girardet (1993, 2004, 2014), Naess (1995), Hall and Pfeiffer (2000), Bithas and Christofakis (2006), Shmelev and Shmeleva (2009), Hall, Buijs, Tan, and Tunas (2010), Dassen, Kunseler, and van Kessenich (2013), Hall (2014), and Martin and Rice (2014). The multidimensional nature of an urban system defines a central analytical approach for the sustainability assessment of cities as used in this paper, namely, the methodology of Multi-Criteria Decision Aid (Roy, 1996), and following an approach outlined in (Shmelev, 2017a).

The Rome declaration adopted at the UN Forum on "Shaping smarter and more sustainable cities: striving for sustainable development goals" in May 2016 declared that "cities need to become smarter, with technological solutions deployed to address a wide range of common urban challenges" of sustainable development (UNECE & ITU, 2016). The EU's European Economic and Social committee considers smart sustainable cities to be a tremendous source of growth, productivity and employment. A smart sustainable city, according to UNECE, is an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social and environmental as well as cultural aspects (UN ECOSOC, 2015).

Cities depend on a wide array of ecosystem processes, functions and ultimately ecosystem services (Bolund & Hunhammar, 1999; Gomez-Baggethun & Barton, 2013; Spangenberg & Settele, 2010). The latter are broadly defined as *economic* (provisioning: water, food, fibre, energy), *ecological* (regulation and maintenance: biogeochemical cycling, soil formation, photosynthesis, pollination, air quality regulation) and *social* (cultural: cultural diversity, educational values, inspiration, aesthetic values) (Shmelev, 2012). Urban economies rely on the natural world and the functioning of ecosystems on the territory of a much larger region than the city itself, making them important systems for ecological economics research (Girardet & Mendonca, 2009). The science of urban sustainability requires therefore the integration of the two approaches, namely, a systemic description of the city, and the analysis of city-ecosystem interactions. A new smart city paradigm could, if applied wisely, assist in reaching the goal of urban sustainability.

In this article, we start by exploring a large database of 90 global cities and search for meaningful relationships between various indicators in the global dataset. We then compare 57 major global cities, for which 20 smart and sustainable indicators were available, to assess sustainability of their performance and identify the sustainability leaders, as well as cities experiencing the strongest sustainability challenges. We use a linear aggregation multidimensional approach characterized by full compensation among criteria. The article aims to test environmental, economic, social and smart policy priorities to assess the balance between sustainability dimensions and provide guidance for policy-makers. The assessment is based on a set of 20 urban sustainability indicators. We conclude with a description of sustainability strategies and policies adopted in the leading cities of our pool, which could help us to understand its success.

The rest of this article is organized as follows. Section 2 discusses the data and the indicators which were used. Section 3 presents the results of regression analysis of linkages among sustainability indicators. Section 4 discusses the application of linear aggregation under economic, social, environmental and smart sustainability priorities to 57 global cities. Section 5 explores the sustainability strategies and policies in the most sustainable cities identified in our research. Section 6 presents conclusions.

2 | INDICATORS FOR SMART SUSTAINABLE CITIES

Existing smart and sustainable cities indicator frameworks include the United Nations Guidelines and Methodologies on Sustainable Development Indicators (UN, 2007), EU Sustainable Development Indicators (European Commission, 2009), a Sustainable Development Indicators Framework (UNECE, 2013), new ISO 37120 standards on Sustainable Development of Communities (ISO, 2014), a Sustainable Development Goals framework (UN, 2015a), and a Smart Sustainable City Indicator Framework (UN ECOSOC, 2015). These frameworks are discussed extensively in a range of comparative reviews (Ahvenniemi, Huovila, Pinto-Seppä, & Airaksinen, 2017; García-Fuentes et al., 2017; Girardi & Temporelli, 2017; Hara, Nagao, Hannoe, & Nakamura, 2016; Kierstead & Leach, 2008; Klopp & Petretta, 2017; Manitiu & Pedrini, 2016; Monfaredzadeh & Berardi, 2015; Pierce, Ricciardi, & Zardini, 2017; Spangenberg, 2002a, 2002b; Spangenberg, 2005; Spangenberg, 2017; Valentin & Spangenberg, 2000).

Recently, there has been a growth of interest in indicator-based sustainability assessments for cities (Michael, Noor, & Figueroa, 2014; Mori & Yamashita, 2015; Shen & Zhou, 2014; Wei, Huang, Lam, & Yuan, 2015; Wei, Huang, Li, & Xie, 2016; Wong, 2015; Yigitcanlar, Dur, & Dizdaroglu, 2015). The indicators following the International Urban Sustainability Indicators List proposed in (Shen, Ochoa, Shah, & Zhang, 2011) include economic characteristics such as income per capita, social and cultural dimensions including unemployment rate, income differentiation rate in the form of a Gini coefficient and higher education level, and, finally, a wide range of ecological-economic or environmental dimensions, including the share of green space, CO_2 emissions, average particulate matter (PM_{10}) concentrations, water use per capita per day, waste generation per capita per day and recycling rates.

Our comparative analysis of the three assessment frameworks (UN SDG indicators; ISO 37120 Sustainable Development of Communities; UNECE-ITU Smart Sustainable City Indicators) has shown a difference in focus, balance between economic, social and environment dimensions, and also some inconsistencies. The UN SDG indicator framework is more focused on the problems of developing countries, and with its 249 indicators that are often defined in an imprecise way, could become unmanageable. The ISO 37120 standard shows more precise definition of indicators, although social and environmental aspects are given slightly greater prominence at the expense of economic and smart indicators. In contrast, the UNECE-ITU Smart Sustainable Cities Indicators framework is better balanced between different dimensions of sustainability, and is formulated with a lot of clarity and a forward-looking strategic vision in mind.

The selection of individual indicators for cities, chosen for the current study, was based on an earlier sustainable cities framework (Shmelev & Shmeleva, 2009), inspired by our dynamic sustainability assessments carried out for countries (Shmelev, 2011, 2017b), and adapted for the urban scale (Shmelev, 2017a). The process of indicator selection for the study was performed in two parts. First, a large set of criteria was analysed, including economic indicators (income per capita at Purchasing Power Parity (PPP), the number of large companies headquartered in the city, creative industries employment), environmental indicators (CO_2 emissions per capita, share of nuclear energy, PM_{10} emissions, water use per capita, waste generation per capita, recycling rates) and socio-cultural indicators (unemployment rate, Gini index of income inequality, life expectancy). After performing a Principal Component Analysis (Shmelev, 2017a), identifying redundant variables and adding relevant dimensions, the set of criteria took its final shape numbering 20 criteria as a result of several iterations.

The cities chosen for our analysis include: in Europe, Amsterdam, Barcelona, Berlin, Copenhagen, Frankfurt, Edinburgh, London, Madrid, Milan, Moscow, Munich, Paris, Rome, Stockholm, St Petersburg, Vienna, Warsaw and Zurich; in North and Central America, Atlanta, Austin, Boston, Denver, Los Angeles, Mexico City, Miami, Montreal, New York, Portland, San Francisco, Toronto, Vancouver and Washington DC; in South America, Bogota, Buenos Aires, Lima, Quito, Rio de Janeiro, São Paulo and Santiago; in Asia, Almaty, Beijing, Delhi, Hong Kong, Istanbul, Mumbai, Seoul, Shanghai, Shenzhen, Singapore, Taipei and Tokyo; in Africa, Johannesburg, Kampala and Nairobi; and in Oceania, Adelaide, Melbourne and Sydney. The criteria for selecting these cities from the database of 90 possible cities were economic importance, environmental impacts and, most importantly, availability of data pertaining to all of the characteristics of interest to us. Our study draws on a wide range of sources including Eurostat (2016), Quah, (2016), Carbon Disclosure Project, (2018), Brookings Institution (2015), Rio de Janeiro (2016), Seoul Metropolitan Government, (2016), city government publications (City of New York, 2012; City of Rio de Janeiro, 2011; GLA, 2016a, b; Mairie de Paris, 2011; San Francisco Department for the Environment, 2016; Singapore, 2017), Siemens European Green City Index (Siemens, 2009), the World Cities Culture Report (Mayor of London, 2014), UN HABITAT (UN HABITAT, 2013) and World Bank publications (World Bank, 2013), and the LSE Going Green Report (LSE Cities, 2013).

Cities are characterized by multidimensional complexity, which we will illustrate by presenting three indicators: income per capita, unemployment and CO_2 emissions for all cities in their standardized form, illustrating economic, social and environmental dimensions (with means subtracted from the raw figures and the results divided by standard deviations). As can seen from Figure 1, the cities differ substantially, for example, Los Angeles has considerably higher unemployment and CO_2 emissions than New York, while it is relatively close to it in terms of income. On the other hand, Sao Paolo and Rio de Janeiro exhibit considerably lower CO_2 emissions level due to the development of hydropower, have a relatively low level of income but much lower unemployment than Berlin or London. Moscow and Beijing have a relatively high income level at PPP and enjoy low unemployment; however, both still show considerable potential in reducing CO_2 emissions.

The final set of smart and sustainable indicators included a range of economic, environmental, social and smart cities indicators following an approach identified by the UNECE and ITU United for Smart and Sustainable Cities initiative (Table 1). Table 1 presents the indicators, with various weightings reflecting different policy priorities, as tested in the multi-criteria assessment section. In each policy priority setting, more emphasis is placed on a particular dimension, economic, social, environmental or smart.

Next, we will illustrate the diversity in sustainability performance of global cities in various individual dimensions (Figures 2–9). As can be seen from Figure 2, cities like Beijing, New York, Los Angeles, Tokyo, Paris, Moscow and London exhibit the highest levels of Gross Regional Product at PPP.

As an example, the geographical spread of the Environment Europe database with particulate matter (PM_{10}) concentrations data is illustrated (Figure 2). PM_{10} concentrations are very high in Delhi, Beijing, Shanghai, Rio de Janeiro and Hong Kong, and they are much lower in Sydney, Toronto, Washington DC, New York, Tokyo, Los Angeles and Berlin.

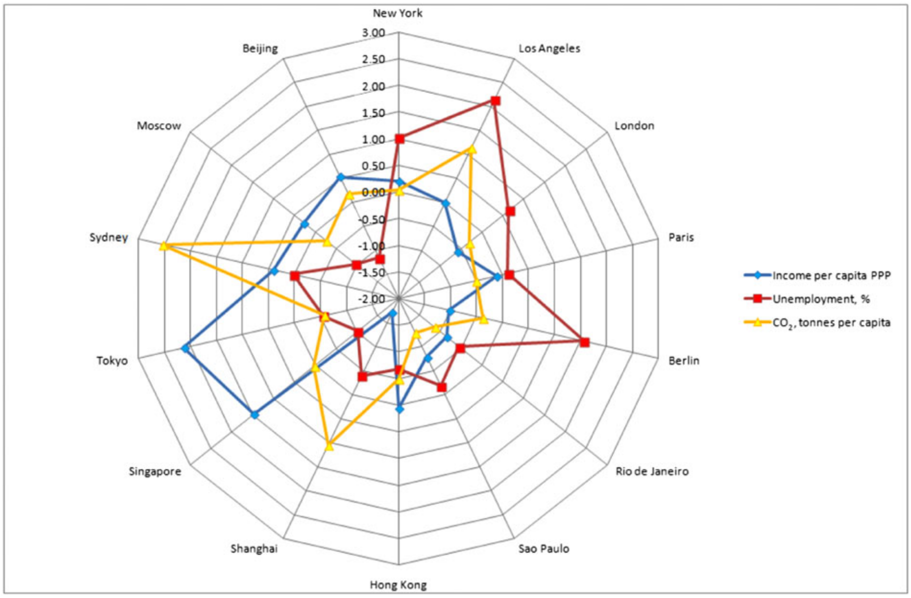

FIGURE 1 Comparative performance of 14 top megacities in economic, social and environmental dimensions for income per capita, unemployment and CO_2 emissions per capita (standardized data, 2013) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Urban smart and sustainable indicator weightings

Type	Abbreviation	Indicator	Equal	Environmental	Economic	Social	Smart
Economic	GRP	gross regional product (PPP, $ million)	0.0625	0.0417	0.1250	0.0417	0.0417
Economic	INCOME	disposable income per head (PPP, 2010 USD)	0.0625	0.0417	0.1250	0.0417	0.0417
Economic	INFLATION	consumer price inflation rate (%)	0.0625	0.0417	0.1250	0.0417	0.0417
Economic	UNEMPLOYMENT	unemployment rate (%)	0.0625	0.0417	0.1250	0.0417	0.0417
Smart	PATENTS	number of patents per thousand inhabitants	0.0625	0.0556	0.0556	0.0556	0.1667
Smart	INTERNET	average broadband internet speed (Mb/c)	0.0625	0.0556	0.0556	0.0556	0.1667
Smart	METRO	number of underground stations per million inhabitants	0.0625	0.0556	0.0556	0.0556	0.1667
Social	LIFE	life expectancy at birth (years)	0.0625	0.0556	0.0556	0.1667	0.0556
Social	EDUCATION	proportion of population aged 24–65 years with a higher education	0.0625	0.0556	0.0556	0.1667	0.0556
Social	GINI	Gini index of income inequality (%)	0.0625	0.0556	0.0556	0.1667	0.0556
Environmental	CO_2	CO_2 emissions per person per year (tonnes)	0.0625	0.0833	0.0278	0.0278	0.0278
Environmental	RENEWABLES	proportion of renewable energy in the energy mix (%)	0.0625	0.0833	0.0278	0.0278	0.0278
Environmental	PM10	PM10 average annual concentration (mg/m3)	0.0625	0.0833	0.0278	0.0278	0.0278
Environmental	WATER	domestic water consumption (m3 per person per year)	0.0625	0.0833	0.0278	0.0278	0.0278
Environmental	WASTE	municipal solid waste (kg per person per year)	0.0625	0.0833	0.0278	0.0278	0.0278
Environmental	RECYCLING	municipal solid waste recycling rate (%)	0.0625	0.0833	0.0278	0.0278	0.0278
	TOTAL		**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

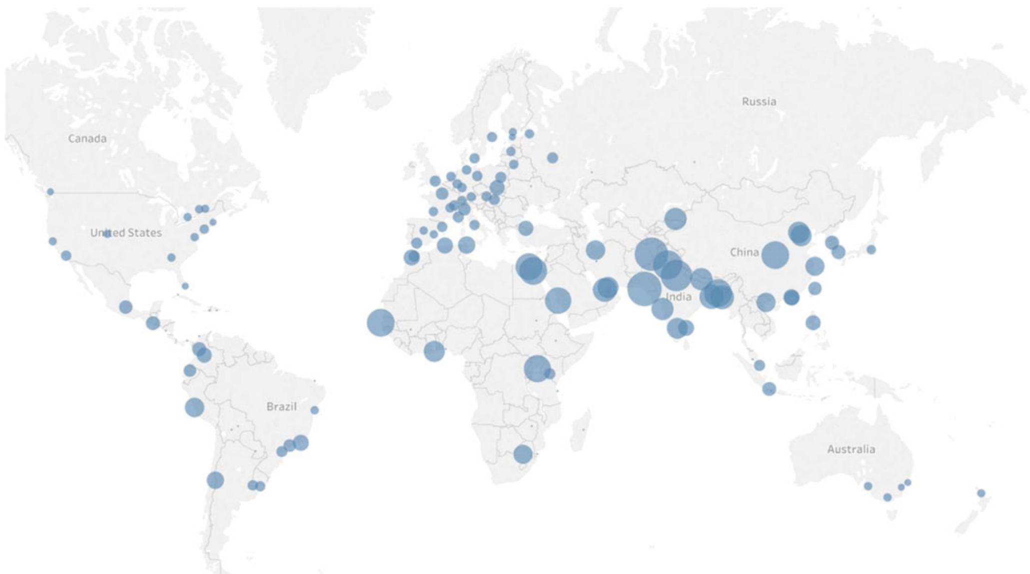

FIGURE 2 PM_{10} concentrations. Source: Environment Europe Sustainable Cities Database (http://environmenteurope.org/), 90 global cities, 2017 [Colour figure can be viewed at wileyonlinelibrary.com]

3 | CROSS-SECTION REGRESSION ANALYSIS

It would be highly beneficial to explore the world cities database from the point of view of interdependencies and trade-offs among various sustainability indicators, to help understand causes for particular performances across the entire pool of cities. Our goal in this section was to test several hypotheses regarding the inter-disciplinary links among urban sustainability dimensions that were emphasized in the UN Guidelines on Sustainable Development Indicators (UN, 2007). We explored a database of world cities, featuring 90+ cities from all inhabited continents, to attempt to see if there is a statistically significant relationship between pairs of indicator variables across the whole spectrum of cities.

The confirmation of our hypothesis of a highly significant correlation between the number of CO_2 emissions and the share of coal, the most carbon-intensive technology at present in the energy mix (Figure 3), reinforces the need for an urgent transformation and decarbonization of the energy sector. Cities such as Sydney, Warsaw, Hong Kong, Denver, Portland, Los Angeles, Washington and Shenzhen have above-average levels of coal in the energy mix and exhibit high per capita CO_2 emissions. On the other hand, cities

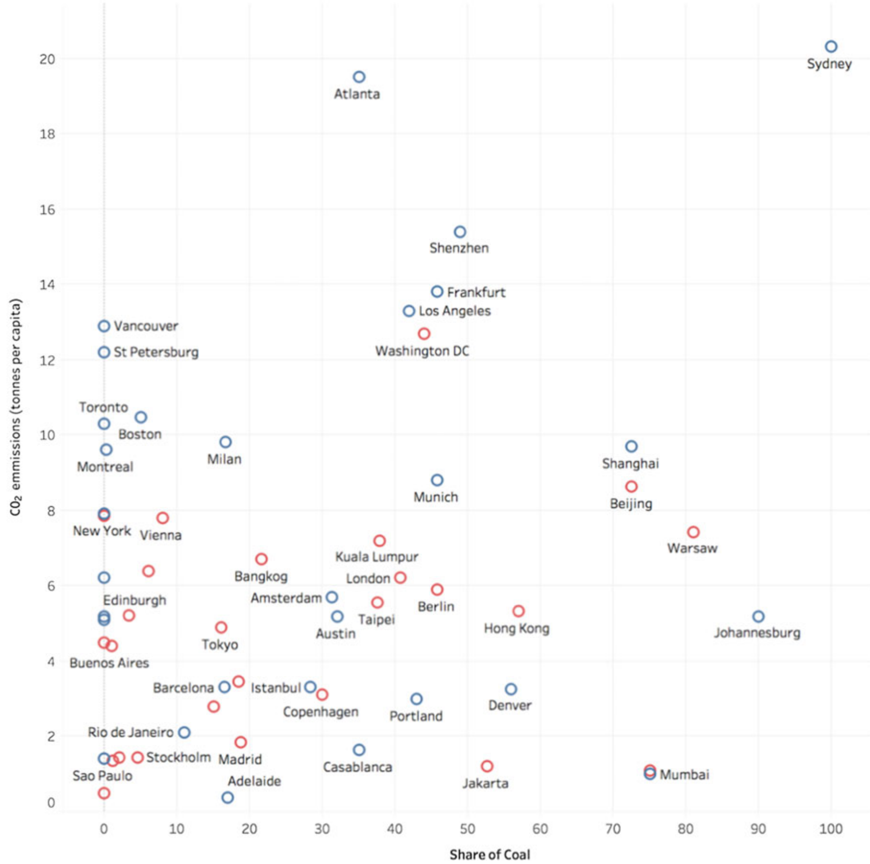

FIGURE 3 Correlation between CO_2 emissions and the share of coal in the energy mix for global cities. Source: Environment Europe Sustainable Cities Database (http://environmenteurope.org/), 90 global cities, 2017 [Colour figure can be viewed at wileyonlinelibrary.com]

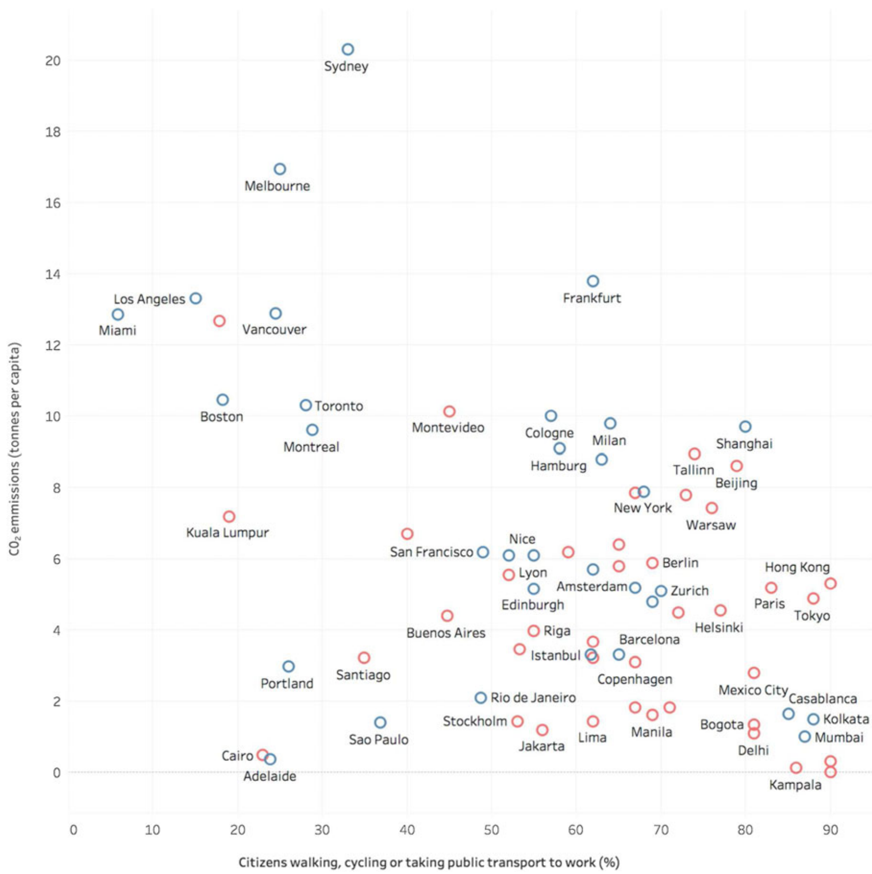

FIGURE 4 Correlation between CO_2 emissions and the share of trips made by walking, cycling and taking public transport for global cities. Source: Environment Europe Sustainable Cities Database (http://environmenteurope.org/), 90 global cities, 2017 [Colour figure can be viewed at wileyonlinelibrary.com]

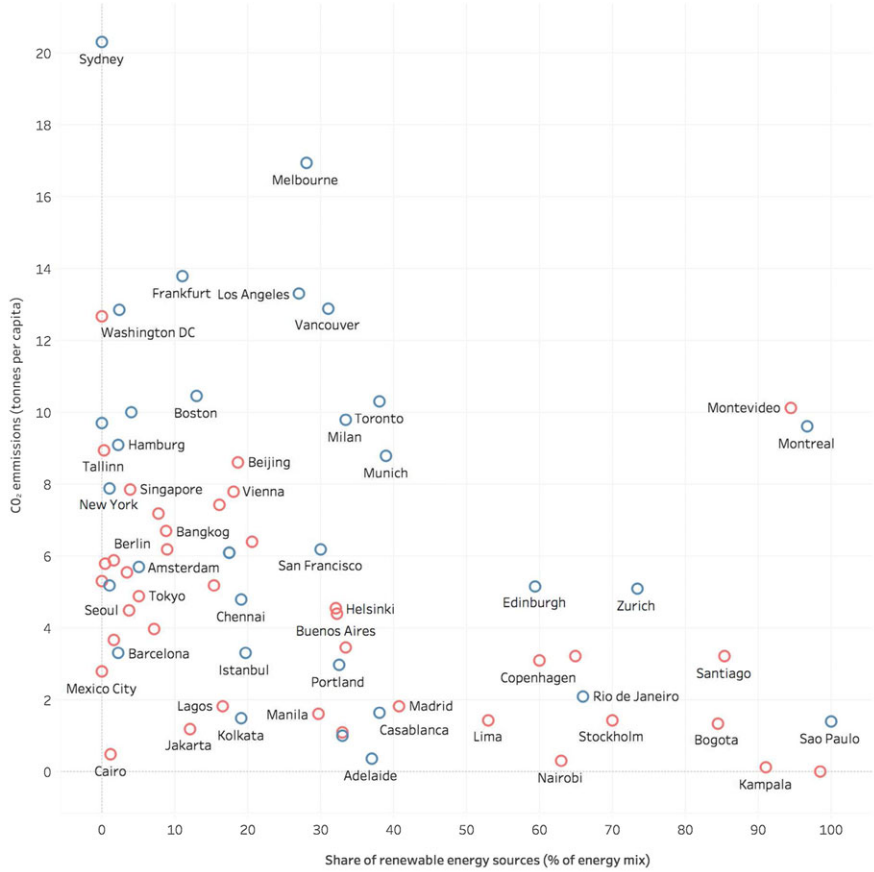

FIGURE 5 Correlation between CO_2 emissions and the share of the renewable energy for global cities. Source: Environment Europe Sustainable Cities Database (http://environmenteurope.org/), 90 global cities, 2017 [Colour figure can be viewed at wileyonlinelibrary.com]

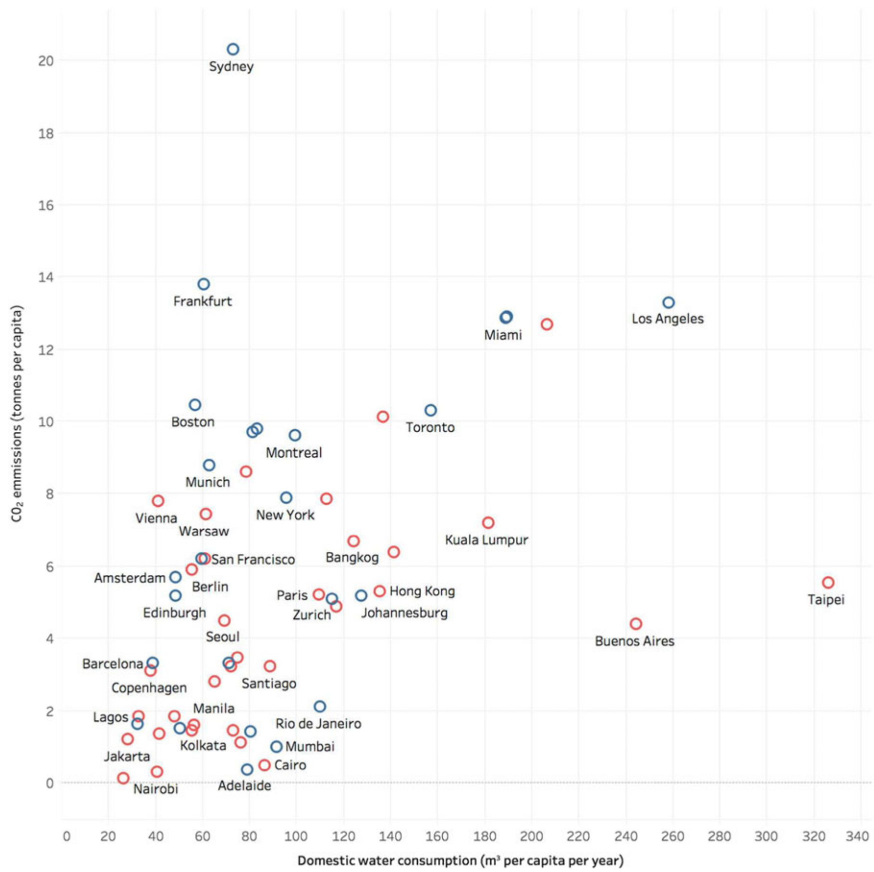

FIGURE 6 Correlation between CO_2 emissions and water consumption for global cities. Source: Environment Europe Sustainable Cities Database (http://environmenteurope.org/), 90 global cities, 2017 [Colour figure can be viewed at wileyonlinelibrary.com]

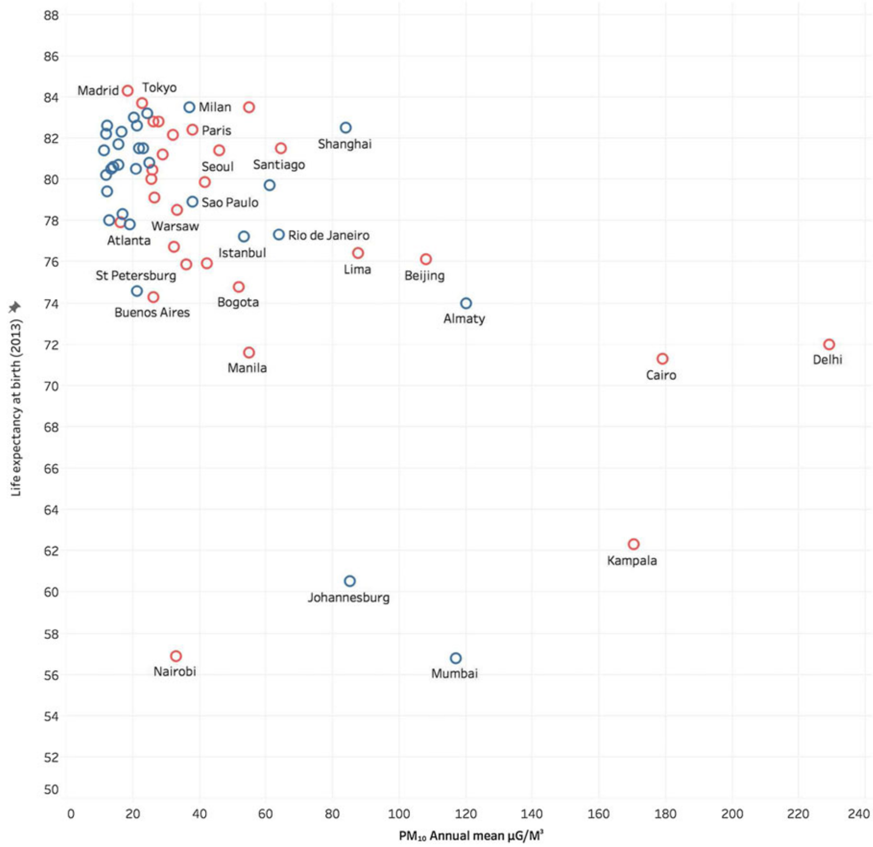

FIGURE 7 Correlation between PM_{10} concentration and life expectancy for global cities. Source: Environment Europe Sustainable Cities Database (http://environmenteurope.org/), 90 global cities, 2017 [Colour figure can be viewed at wileyonlinelibrary.com]

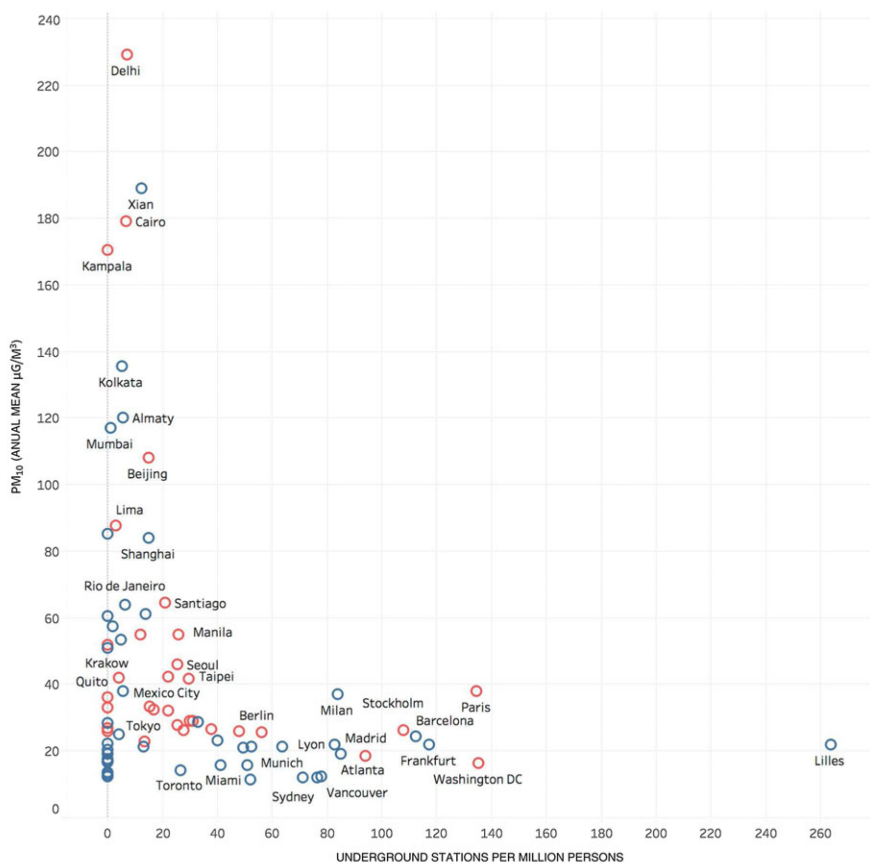

FIGURE 8 Correlation between availability of underground stations per million inhabitants and PM_{10} concentrations for global cities. Source: Environment Europe Sustainable Cities Database (http://environmenteurope.org/), 90 global cities, 2017 [Colour figure can be viewed at wileyonlinelibrary.com]

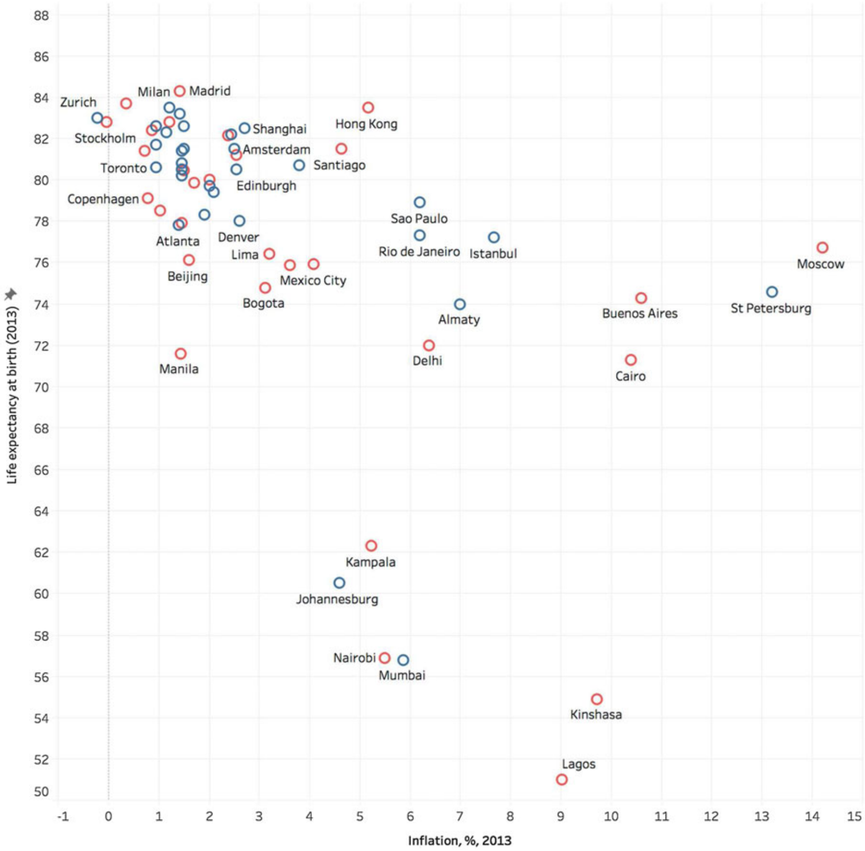

FIGURE 9 Correlation between inflation and life expectancy for global cities. Source: Environment Europe Sustainable Cities Database (http://environmenteurope.org/), 90 global cities, 2017 [Colour figure can be viewed at wileyonlinelibrary.com]

such as Sao Paolo, Rio de Janeiro, Bogota, Quito, Madrid, Adelaide, Copenhagen and Rome have a relatively low share of coal in the energy mix and lower levels of CO_2 emissions per capita.

Coefficients				
Term	Value	Std. Err.	t-value	p-value
Share of coal	0.0727687	0.0307517	2.36633	0.023467
intercept	5.16234	0.993979	5.19362	< 0.0001

A significant correlation between CO_2 emissions and the share of trips made by walking, cycling and public transport has been confirmed (Figure 4), which enriches our understanding of this wonderful urban planning tool for improving air quality and making the cities greener.

Coefficients				
Term	Value	Std. Err.	t-value	p-value
Citizens walking, cycling or taking public transport to work (%)	−0.0802487	0.0222075	−3.61359	0.0007453
intercept	11.0772	1.32395	8.36673	< 0.0001

Cities such as Stockholm, Mumbai, Bogota, Delhi, Mexico City, Paris, Amsterdam, Seoul, Barcelona, Sao Paolo, Berlin, Singapore and Moscow have a significant percentage of trips made by walking, cycling and using public transport, and are associated with lower per capita CO_2 emissions. On the other hand, cities such as Sydney, Shenzhen, Almaty, Los Angeles, Miami, Kuala Lumpur, Boston, Vancouver and Toronto rely on a private car in a much more pronounced way, and therefore have significantly higher CO_2 emissions per capita.

The role of renewable energy in reducing CO_2 emissions in global cities has been confirmed at a very high level of statistical significance (Figure 5). This clearly reinstates the tendency in cities like Sao Paolo, Bogota, Montreal, Stockholm, Rio de Janeiro, Zurich and Copenhagen, which are largely powered by hydro-energy and have lower per capita CO_2 emissions. At the same time, cities like Sydney, Atlanta, Almaty, Frankfurt, Miami, St Petersburg, Shanghai, Boston, Los Angeles, Vancouver and Shenzhen that have lower levels of renewables in the energy mix, tend to exhibit higher per capita CO_2 emissions.

Coefficients				
Term	Value	Std. Err.	t-value	p-value
Share of renewable energy sources (% of energy mix)	−0.0744972	0.0217927	−3.41845	0.001205
intercept	8.66991	0.845428	10.2551	< 0.0001

The hypothesis of a strong water-energy nexus, whereby larger CO_2 emissions tend to go hand in hand with higher water consumption, has been confirmed. Figure 6 presents an illustration of such a phenomenon and shows cities like Los Angeles, Almaty, Atlanta, Miami, Toronto and Kuala Lumpur using larger amounts of water with higher per capita CO_2 emissions. At the same time, cities like Bogota, Lima, Lagos, Madrid, Adelaide, Barcelona, Copenhagen, Seoul and Rome exhibit lower levels of per capita CO_2 emissions accompanied by lower water consumption.

Coefficients				
Term	Value	Std. Err.	t-value	p-value
Domestic water consumption (m^3 per capita per year)	0.0279766	0.0091705	3.05071	0.0034178
intercept	3.57072	1.07541	3.32035	0.0015458

The hypothesis of a strong statistical link between life expectancy and PM_{10} concentrations presented in Figure 7 echoes the recent WHO report on ambient air pollution and the diseases it causes (WHO, 2016). Cities with lower PM_{10} concentrations have significantly higher life expectancy, which confirms the WHO estimates. On average, 10 extra micrograms of PM_{10} per cubic metre of air means a lowering of one's life expectancy by 0.7 years. Cities such as Delhi, Kampala, Mumbai, Cairo and Johannesburg exhibit considerably lower levels of life expectancy against a background of higher PM_{10} concentrations. At the positive end of the spectrum, Tokyo, Madrid, Stockholm and Copenhagen have a higher average life expectancy and lower levels of PM_{10}.

Coefficients				
Term	Value	Std. Err.	t-value	p-value
PM_{10} (annual mean μg/m^3)	−0.0760637	0.0156302	−4.86647	< 0.0001
intercept	81.5098	0.978429	83.3068	< 0.0001

The correlation between PM_{10} concentrations and availability of underground stations depicted in Figure 8 illustrates one possible way of tackling high PM_{10} pollution in cities like Bogota, Delhi, Xian, Cairo, Kampala, Mumbai and Kolkata, which do not currently have an underground network. Our hypothesis on the existence of such a relationship has been confirmed at a high level of statistical significance. In this regard, cities such as Washington DC, Paris, Barcelona, Lille, Frankfurt and Madrid show the way by offering their residents a diversified and reliable underground system, which could be responsible for avoiding unnecessary PM_{10} emissions associated with private transportation.

Coefficients				
Term	Value	Std. Err.	t-value	p-value
Underground stations per million persons	−0.288601	0.110996	−2.60011	0.0112728
intercept	54.7402	6.09773	8.97715	< 0.0001

On the other hand, often such neglected phenomena as inflation can have a profound effect on life expectancy through stress (Figure 9). Our hypothesis regarding such a statistical link has been confirmed. Cities such as Lagos, Kinshasa, Moscow, St Petersburg, Buenos Aires and Cairo exhibit a high level of inflation and lower levels of life expectancy. On the other hand, Tokyo, Milan, Madrid, Barcelona, Paris, Seoul, Toronto, Copenhagen and Vienna show lower levels of inflation and higher levels of life expectancy.

Coefficients				
Term	Value	Std. Err.	t-value	p-value
Inflation, % (2013)	−1.28743	0.255917	−5.03064	< 0.0001
intercept	81.6719	1.20259	67.9131	< 0.0001

4 | SUSTAINABILITY ASSESSMENT: LINEAR AGGREGATION

As a first step in the multidimensional sustainability assessment, we carried out a linear aggregation with different weights representing various policy priorities. The total number of cities, for which enough data on the respected sustainability indicators was available was 57. This set includes the A+++, A++ and A+ cities, the most important global cities representing Europe, Africa, Asia, North, Central and South America, and Oceania. The cities in question represent 6.7% of Europe's population, 3.2% of the population of Asia, 5.4% of the North and Central American population, 10.5% of the South American population, 26.1% of the population of Oceania, and 0.7% of the African population; this indicates some imbalance, which we are planning to address in the future by increasing the share of Asian and African cities in the database. The cities in the Environment Europe database includes both of the A++ cities, London and New York, and most of the A+ cities, including Singapore, Shanghai, Tokyo, Hong Kong, Bejing and Paris, as well as the most significant A-, B+, B and B- cities from other regions.

The linear aggregation assumed perfect substitutability among sustainability criteria and represented a weak sustainability case. Several different policy priorities were applied, placing the emphasis on economic, social, environmental or smart dimensions through various weightings. The results of the assessment applied to 57 global cities are presented in Table 2.

The results show that for environmental priorities the top five cities are San Francisco, Stockholm, Seoul, Copenhagen and Zurich, and that for smart policy priorities the leading cities are Stockholm, San Francisco, Paris, Tokyo and Boston. San Francisco leads for environmental and economic priorities, and Stockholm leads for social and smart priorities. Seoul is in third place globally for environmental priorities, second for economic priorities, fifth for social priorities and eighth for smart policy priorities, which is an extremely strong overall performance. Copenhagen occupies fourth place for economic priorities, eleventh position for economic priorities, is second for social priorities and seventh for smart policy priorities. London is at twenty-fifth place for environmental priorities, twenty-sixth for economic priorities, is twenty-first for social priorities and thirtieth for smart policy priorities. Washington DC occupies twenty-ninth place for environmental priorities, is eighth for economic priorities, twenty-ninth for social priorities, and eleventh for smart policy priorities.

The worst performing cities in our database are Johannesburg, Almaty, Delhi, Buenos Aires and Nairobi for environmental priorities, Nairobi, Buenos Aires, Johannesburg, Delhi and Kampala for economic priorities, Johannesburg, Nairobi, Mumbai, Delhi and Rio de Janeiro for social priorities, and Johannesburg, Nairobi, Delhi and Kampala for smart priorities.

5 | THE MOST SUSTAINABLE GLOBAL CITIES

In this section we explore some of the most sustainable and smart cities globally and attempt to explain how they achieved their remarkable

TABLE 2 Multidimensional sustainability assessment of global cities under environmental, economic, social and smart priorities, linear aggregation

	Equal priorities		Environmental priorities		Economic priorities		Social priorities		Smart priorities	
	City	Score	City	Score	City	Score	City	Score	City	Score
1	San Francisco	0.73	San Francisco	0.745884997	San Francisco	0.708003312	Stockholm	0.800145459	Stockholm	0.734842073
2	Stockholm	0.72	Stockholm	0.735417008	Tokyo	0.697652042	Copenhagen	0.739615123	San Francisco	0.659201186
3	Seoul	0.68	Seoul	0.685249975	Seoul	0.696152134	Zurich	0.725674633	Paris	0.619604064
4	Tokyo	0.67	Copenhagen	0.6842292	Stockholm	0.675517709	Munich	0.716716327	Tokyo	0.605628111
5	Copenhagen	0.66	Zurich	0.67217179	Washington DC	0.625993804	Seoul	0.711239543	Boston	0.602802376
6	Zurich	0.65	Tokyo	0.66247683	Zurich	0.622858441	San Francisco	0.710184418	Frankfurt	0.593562987
7	Munich	0.65	Munich	0.66018521	Paris	0.62092934	Madrid	0.708767143	Copenhagen	0.58570181
8	Frankfurt	0.62	Montreal	0.639838834	Munich	0.619687801	Tokyo	0.701973518	Seoul	0.578860239
9	Madrid	0.62	Madrid	0.637499828	New York	0.61594733	Vancouver	0.688488867	Taipei	0.569712512
10	Paris	0.61	Frankfurt	0.624050907	Boston	0.611629443	Toronto	0.683852649	Munich	0.56890388
11	Montreal	0.61	Amsterdam	0.618056991	Copenhagen	0.608714892	Amsterdam	0.682670552	Washington DC	0.553811694
12	Vancouver	0.60	Toronto	0.617863979	Taipei	0.602676238	Barcelona	0.679793758	Barcelona	0.540994193
13	Singapore	0.60	Singapore	0.611425822	Frankfurt	0.600119405	Frankfurt	0.670926054	Singapore	0.53526509
14	Toronto	0.60	Vancouver	0.611411576	Singapore	0.598588401	Edinburgh	0.667160688	Zurich	0.528210603
15	Amsterdam	0.60	Paris	0.607608958	Beijing	0.59640179	Vienna	0.662481827	Madrid	0.527752497
16	Boston	0.60	Adelaide	0.603481526	Austin	0.586246138	Montreal	0.660955734	Vancouver	0.50542939
17	Taipei	0.59	Edinburgh	0.598758802	Vancouver	0.582418071	Taipei	0.6569491	**Shenzhen**	0.50272304
18	Vienna	0.58	Vienna	0.598268302	Portland	0.581904083	Berlin	0.634732411	Amsterdam	0.498058688
19	Barcelona	0.58	Milan	0.597465354	Toronto	0.575988627	Warsaw	0.633965376	Austin	0.483968156
20	Milan	0.58	Barcelona	0.593772608	Denver	0.567601987	Sydney	0.622556009	Vienna	0.481498643
21	Washington DC	0.58	Taipei	0.592371942	Madrid	0.564664119	London	0.620502525	New York	0.477920684
22	Sydney	0.57	Sydney	0.59008489	Montreal	0.561176363	Milan	0.617602012	Milan	0.469122942
23	Edinburgh	0.57	Berlin	0.589412927	Milan	0.557420295	Paris	0.614817019	Berlin	0.464880591
24	Adelaide	0.57	Boston	0.588554207	Amsterdam	0.554365679	Shanghai	0.600154385	Sydney	0.464391224
25	New York	0.57	London	0.578254515	Vienna	0.552477483	Boston	0.596544585	Hong Kong	0.455196953
26	Berlin	0.57	Portland	0.576392478	Atlanta	0.552181102	Adelaide	0.591568055	Portland	0.454998553
27	Portland	0.57	Rome	0.569579517	London	0.549935855	Austin	0.589318111	Montreal	0.454249488
28	London	0.56	Warsaw	0.565584215	Sydney	0.549063819	Rome	0.585334325	Toronto	0.452383872
29	Austin	0.56	Washington DC	0.565520018	**Shenzhen**	0.545464616	Washington DC	0.581151193	Atlanta	0.450998826
30	Warsaw	0.55	New York	0.565035794	Los Angeles	0.544369341	Portland	0.574510999	London	0.432838965
31	Beijing	0.55	Austin	0.55472764	Barcelona	0.54258191	**Shenzhen**	0.573266165	Los Angeles	0.410511808
32	**Shenzhen**	0.55	**Shenzhen**	0.547207327	Melbourne	0.541434773	Singapore	0.568662475	Beijing	0.404308052
33	Rome	0.54	Beijing	0.543157107	Adelaide	0.534777429	New York	0.556414778	Denver	0.39812501
34	Denver	0.53	Denver	0.533315352	Edinburgh	0.532754009	Melbourne	0.555410767	Warsaw	0.393872008

(Continues)

TABLE 2 (Continued)

	Equal priorities		Environmental priorities		Economic priorities		Social priorities		Smart priorities	
	City	Score	City	Score	City	Score	City	Score	City	Score
35	Los Angeles	0.52	Los Angeles	0.53326136	Berlin	0.528497293	Denver	0.550529334	Edinburgh	0.391991023
36	Hong Kong	0.51	Sao Paulo	0.531032486	Warsaw	0.520810855	Beijing	0.526295598	Shanghai	0.379785135
37	Shanghai	0.50	Bogota	0.53062545	Hong Kong	0.51080279	Atlanta	0.526069018	Rome	0.376887078
38	Atlanta	0.50	Hong Kong	0.521778257	Rome	0.50842732	Los Angeles	0.519841336	Miami	0.37510133
39	Melbourne	0.49	Quito	0.50368792	Shanghai	0.497864078	Moscow	0.504114777	Adelaide	0.367893436
40	Sao Paulo	0.49	Shanghai	0.502713837	Miami	0.491059448	St Petersburg	0.502147951	Melbourne	0.36583582
41	Bogota	0.48	Lima	0.493246607	Sao Paulo	0.449451189	Hong Kong	0.49099525	Moscow	0.345222003
42	Quito	0.46	Melbourne	0.489935071	Moscow	0.441644585	Almaty	0.460732654	St Petersburg	0.321464479
43	Lima	0.46	Kampala	0.479298573	Lima	0.439305072	Miami	0.451267446	Sao Paulo	0.319247299
44	Moscow	0.46	Moscow	0.47907333	Santiago	0.433688092	Sao Paulo	0.441283691	Mexico City	0.297696202
45	Miami	0.44	Atlanta	0.475945113	Mexico City	0.430961106	Lima	0.437054842	Santiago	0.29578621
46	Mexico City	0.43	St Petersburg	0.461413807	Bogota	0.428122562	Santiago	0.436593786	Lima	0.278749801
47	St Petersburg	0.43	Rio de Janeiro	0.454332021	Quito	0.421538867	Istanbul	0.423974389	Bogota	0.278007389
48	Kampala	0.43	Mexico City	0.452530326	Rio de Janeiro	0.403275716	Mexico City	0.412340806	Istanbul	0.273777439
49	Santiago	0.43	Istanbul	0.449706691	Almaty	0.389712414	Bogota	0.411217219	Almaty	0.271746822
50	Rio de Janeiro	0.42	Santiago	0.443018098	Istanbul	0.378744514	Quito	0.402072178	Rio de Janeiro	0.267282964
51	Istanbul	0.42	Miami	0.425037308	St Petersburg	0.378252185	Buenos Aires	0.377719961	Quito	0.267106988
52	Mumbai	0.39	Mumbai	0.421730586	Mumbai	0.369616653	Kampala	0.377711632	Buenos Aires	0.258732775
53	Buenos Aires	0.39	Nairobi	0.417263843	Buenos Aires	0.367053304	Rio de Janeiro	0.376011815	Kampala	0.244507359
54	Almaty	0.38	Buenos Aires	0.414663003	Kampala	0.362869699	Delhi	0.319621638	Mumbai	0.225173887
55	Delhi	0.38	Delhi	0.401285845	Delhi	0.362641389	Mumbai	0.305548895	Delhi	0.224037724
56	Nairobi	0.34	Almaty	0.376863919	Johannesburg	0.279105566	Nairobi	0.234899074	Nairobi	0.176755155
57	Johannesburg	0.29	Johannesburg	0.323259721	Nairobi	0.232543873	Johannesburg	0.168994392	Johannesburg	0.157769727

Red = North America; Blue = Europe; Pink = Asia; Green = South America; Yellow = Africa; Dark Blue = Australia and Oceania.

success. Among the most successful cities are San Francisco, the high-technology and sustainability hub in the most economically successful state of the USA, California, which is equivalent to the economy of France in size. We also examine two national capitals, Stockholm and Seoul (Figure 10). Two other national capitals, Copenhagen and Tokyo, follow close behind.

5.1 | San Francisco

San Francisco leads our ranking in Economic and Environmental dimensions worldwide. It has featured as a top global city in the Global Cities Index 2017 by AT Kearney. The World Economic Forum places San Francisco second in the world for Technology in 2017. The Strategic Plan of San Francisco for 2016–2020 has a mission "to provide solutions that advance climate protection and enhance quality of life for all San Franciscans". The Strategic Plan has five goals: (i) promoting Healthy Communities and Ecosystems; (ii) Leading on Climate Action; (iii) Strengthening Community Resilience; (iv) Eliminating Waste; and (v) Amplifying Community Action.

Goal 1 has the target to foster healthy and sustainable communities through science, with an emphasis on supporting San Francisco's most vulnerable populations; it has these subgoals:

- Increase adoption of safer alternatives to harmful products and materials
- Support residents, businesses and city staff in limiting the use of toxic and hazardous products, practices and materials
- Partner with key stakeholders to ensure sustainability initiatives are equitable and accessible
- Leverage the purchasing power of municipal operations to advance markets for green products and services
- Lead and leverage inter-agency efforts to green San Francisco's built and natural environments
- Maximize carbon sequestration through natural ecosystems
- Support sustainable and healthy food options for all individuals and families in San Francisco, especially the food insecure.

Goal 2 has an active target to reduce greenhouse gas emissions by 40% by 2025; it has these subgoals:

- maximize energy efficiency in existing buildings
- reduce dependency on single occupancy vehicles by improving access to sustainable and affordable modes of transportation
- commit to ambitious carbon reduction targets across city agencies
- continue to share San Francisco's practices and lessons to show the world what is possible
- decarbonize the energy used for heating and cooling buildings
- accelerate the shift to 100% renewable grid electricity by 2030 and maximize local onsite generation of renewable electricity through policy development and investment
- decarbonize the transport sector by facilitating deployment of electric and zero-emission vehicles.

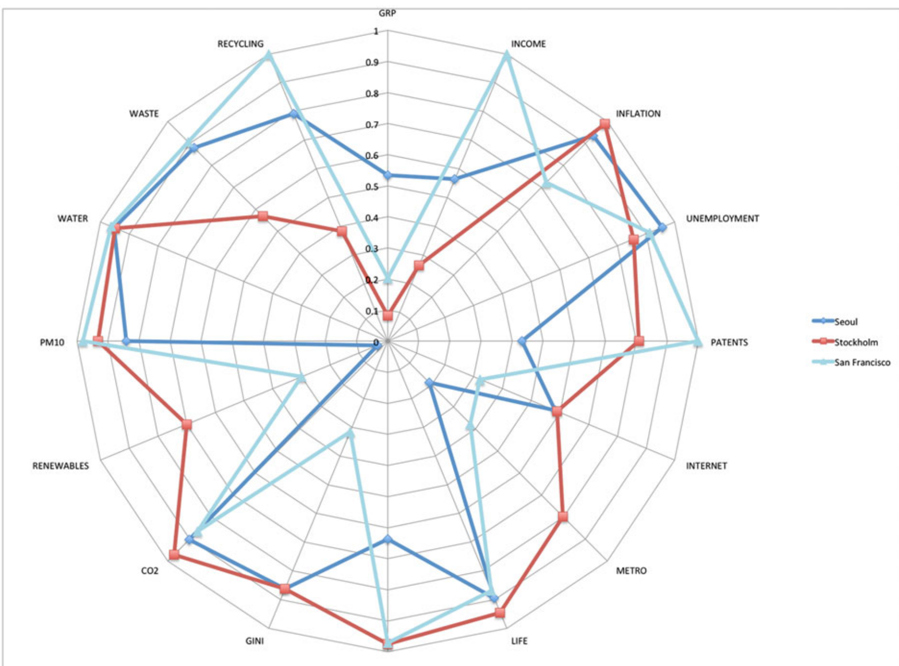

FIGURE 10 Comparison of three of the most successful cities globally, San Francisco, Stockholm and Seoul. A greater distance from the centre represents a better performance on a particular indicator, Abbreviations: CO_2, CO_2 emissions per person per year (tonnes); EDUCATION, proportion of population aged 24–65 years with a higher education; GINI, Gini index of income inequality (%); GRP, gross regional product (PPP, $ million); INCOME, disposable income per head (PPP, 2010 US $); INFLATION, consumer price inflation rate (%); INTERNET, average broadband internet speed (Mb/c); LIFE, life expectancy at birth (years); METRO, number of underground stations per million inhabitants; PATENTS, number of patents per thousand inhabitants; PM_{10}, PM_{10} average annual concentration (mg/m^3); RECYCLING, recycling rate (%); RENEWABLES, share of renewable energy sources; UNEMPLOYMENT, unemployment rate (%); WASTE, municipal solid waste (kg per person per year); WATER, domestic water consumption (m^3 per person per year). [Colour figure can be viewed at wileyonlinelibrary.com]

Goal 3 focuses on supporting economically resilient communities; it has these subgoals:

- Keep small businesses and community-based organizations in San Francisco by minimizing costs associated with energy use, water use and waste generation
- Reduce the cost of living in San Francisco by ensuring cost-effective energy-efficient upgrades of all housing, with a special focus on affordable housing
- Create jobs and economic opportunities by keeping sustainability investments in local communities
- Increase equitable distribution and installation of local renewable energy and battery storage
- Connect those communities most adversely impacted by environmental injustices with resources that enable them to become more resilient to the impacts of climate change
- Make San Francisco's infrastructure, landscapes and neighbourhoods resilient to climate change, and coordinate with other city agencies and jurisdictions on adaptation planning and community engagement to ensure everyone has a seat at the table.

Goal 4 aims to achieve zero waste and work towards closing landfills serving San Francisco; it has these subgoals:

- Increase participation in recycling and composting programmes
- Expand accessibility and the structure of programmes for collecting hazardous products
- Modernize San Francisco's refuse collection and process infrastructure
- Increase reuse and recycling of construction and demolition
- Prevent food waste
- Reduce consumption of single-use items and expand the use of sustainable packaging materials.

Goal 5 aims to build a shared culture of environmental stewardship across San Francisco. It aims to reflect stakeholders' values, needs, and everyday lives in departmental programmes offered and via environmental action, challenging businesses and local influencers to commit to meaningful action on climate strategy, aligning programme services with partners across city departments to maximize impact and reduce confusion, supporting and growing local environmental leaders, particularly in communities that have historically been under-represented in the environmental movement, providing grants and resources to a wide range of organizations in order to increase reach and collaboration, increasing personal actions that reduce impacts while preparing for climate change, and increasing the funding pool available to community groups for neighbourhood environmental work by expanding the carbon fund grant programme.

San Francisco is one of the world leaders on recycling (80%), generating very small amounts of municipal solid waste per person (195.4 kg per year). Indeed, 49% of the trips made by citizens are carried out by walking, cycling or using public transport. San Francisco generates 6.2 tonnes of CO_2 per person per year and generates 30% of its energy through renewable sources. In the field of air quality, San Francisco exhibits low levels of PM_{10} pollution at 15.77 μg/m^3, which is within the WHO limit of 20 μg/m^3. It has a reasonably diverse system of underground public transport.

Economically, San Francisco is one the most vibrant places in the world. With high per capita income of 88 518 US $ (at PPP in 2010 prices), inflation is low at 3.8%, and the unemployment rate is 4.4%, which is three times lower than that of Los Angeles. San Francisco is a world innovation hub with 3.24 patents registered per 1000 inhabitants, which is higher than Boston. Income differentiation in San Francisco is high, illustrated by a Gini index of income inequality of 0.51. Such a relatively high income inequality could limit San Francisco's performance in the social dimension.

5.2 | Stockholm

Analysis of Stockholm's performance as a sustainable city has been the focus of our recent work. Our research, as well as several other metrics, including the European Green City Index compiled by Siemens in 2009, highlight the very strong position of Stockholm compared with other capital cities. Stockholm has received the prestigious prize of European Green Capital in 2010, awarded by experts following a detailed assessment of cities' performance. The city of Stockholm adopted the Environmental Program for 2016–2019 based on complementarity between environmental protection and human needs. The six priority areas of this programme are: (i) sustainable energy use, (ii) environmentally friendly transport, (iii) sustainable land and water use, (iv) resource-efficient recycling, (v) a non-toxic Stockholm, and (vi) a healthy indoor environment.

Our research shows that, along with a serious concern about the environment, Stockholm exhibits extremely strong economic performance. Sweden is consistently ranked high in the World Economic Forum Global Competitiveness Index. Sweden is a very open economy and outperforms USA, Japan and Brazil by attracting ~4.7% of GDP in foreign direct investment per annum. At the same time, it invests ~3.7% of GDP in research and development, which is considerably higher than the EU average of 1.8%. Sweden and Stockholm managed to decouple economic development from the growth in CO_2 emissions as a result of technological modernization in the 1970s with the extensive use of hydropower and nuclear energy, as well as successful application of environmental taxes since 1991 (Shmelev & Speck, 2018). Stockholm aims to be fossil fuel-free by 2050 and is actively involved in new programmes on green urban transport.

Despite rather modest per capita disposable income of 23.456 US $ (at PPP in 2010 prices), which is higher than that of London, Berlin, Madrid, Rome and Copenhagen, and slightly higher than that of Vienna, but lower than that of Paris, Frankfurt, Zurich, Munich and Moscow, Stockholm has been capable of focusing on the qualitative aspects of development. The Stockholm economy is largely innovation-based, with the number of new patents registered (2.62 per 1000 inhabitants) higher than that of all other regional European centres, including technological giants like Copenhagen, Munich and

Zurich. Stockholm outperforms Tokyo, but is at a lower level than Shenzhen, Taipei, Boston and San Francisco. At the same time Stockholm is characterized by very low inflation, in fact, deflation at 0.04%. Unemployment in Stockholm has been recorded at 7.09%, which is lower than the rate for Amsterdam, London, Rome, Berlin and Madrid. Unemployment which is lower than the rate in Stockholm is observed in Copenhagen, Frankfurt, Zurich, Munich, Boston and San Francisco. The level of higher education attained in Stockholm is 58% for all of those residents aged 25–64 years. This is higher than Berlin, Rome, London, Amsterdam, Paris and Munich. In Asia, Stockholm compares favourably at the education level with Seoul, Shanghai and Beijing. In the USA, Stockholm outperforms San Francisco, Washington DC and Boston.

Stockholm, representing the Nordic governance model, is characterized by a high level of taxation (as % of GDP) and a reasonably low Gini index of income inequality (0.3). This is a level very similar to that of Barcelona, Amsterdam and Seoul, is slightly higher than Tokyo and Berlin, but considerably lower than that of Hong Kong, Singapore, Beijing, San Francisco, Washington DC and New York.

In the environmental dimension, Stockholm is characterized by a very distinct position among world cities on certain issues: for example, its leading CO_2 emissions, at 1.44 tonnes per capita, outperforms such world capitals as Madrid, Copenhagen, Barcelona, Rome, Berlin, London and Moscow. Comparison with Asian cities reaffirms the leading position of Stockholm, with CO_2 emissions approximately three times lower than Seoul and more than three times lower than Tokyo and Hong Kong, and considerable lower than in Singapore, Beijing and Shanghai. Among American cities, San Francisco, the regional leader, exhibits CO_2 emissions over four times higher than Stockholm; New York, Washington and Boston are left far behind.

One of the possible reasons for such low CO_2 emissions in Stockholm could be its active reliance on renewable energy. Stockholm occupies one of the leading positions in Europe on share of renewables in the energy mix (70%), following Zurich. Stockholm's performance on renewables is considerably better than other European cities including Copenhagen, Edinburgh, Madrid, Rome, Moscow, Vienna, Paris, London and Amsterdam. On the other hand, according to the data regarding the share of all trips made by walking, cycling and using public transport, Stockholm is unfortunately not in the lead, trailing Vienna, Madrid, Moscow, Amsterdam and London at a modest level of 53%. For comparison, Asian cities like Singapore, Seoul, Beijing, Shanghai, Tokyo and Hong Kong perform better, while American cities like San Francisco and New York are at a similar level, and Los Angeles and Washington DC perform much poorer.

Another important parameter for explaining low CO_2 emission levels is infrastructure, which affords the use of public transport by residents. In this regard, Stockholm is characterized by a highly diversified underground network with 108 underground stations per 1 000 000 inhabitants (million inhabitants). This is better than other European cities such as Madrid, Amsterdam, London, Rome and Berlin, but not Paris. Compared with Stockholm, the Asian cities Kuala Lumpur, Seoul, Singapore, Shanghai, Beijing and Tokyo have considerably fewer stations per 100 000 inhabitants. For comparison, in the USA the leader is Washington DC (the only city outperforming Stockholm), followed by Boston, San Francisco, New York, and Los Angeles, which has a very small underground system.

Air quality in Stockholm is at a good European level with an average annual concentration of PM_{10} at 26 μg/m^3, which is nevertheless higher than the maximum recommended by WHO (20 μg/m^3). Better air quality is observed in such European cities as Edinburgh, Madrid, Zurich, Amsterdam and Vienna; it is worse in London and Paris. In Asia, air quality is better in Tokyo, but it is worse in Singapore, Hong Kong, Shanghai and Beijing. In American cities, air quality tends to be better, for instance in San Francisco, Washington, New York and Los Angeles.

In the field of circular economy, Stockholm generates a rather large amount of municipal solid waste of 597 kg/person per year, 31% of which is recycled. Other European cities practise less resource-intensive lifestyles (e.g. Madrid, Amsterdam, Berlin, London, Paris and Vienna). In Asia, Tokyo generates less than half the municipal solid waste person per year compared with Stockholm; Seoul, Shanghai, Singapore, Beijing and Hong Kong generate much less, but Kuala Lumpur generates considerably more. In comparison, San Francisco generates almost three times less, Washington DC nearly half as much, and New York produces a similar amount; Los Angeles produces slightly more and Boston produces considerably more. Recycling rates are lower than Stockholm in Madrid, Rome, Paris and Copenhagen, and are higher in Vienna, London, Berlin and Amsterdam. In Asia, recycling in Beijing is slightly lower (30%), and in Hong Kong (39%), Singapore (61%) and Seoul (63.5%), considerably higher than in Stockholm. In the USA, New York recycles 27% of its municipal solid waste, and Washington recycles 26%; however, Los Angeles recycles 76.4% and San Francisco recycles 80%.

5.3 | Seoul

In November 2017, the Metropolitan Government of Seoul adopted 17 Sustainable Development Goals and 96 targets. The Seoul Plan 2030, an urban planning document, covers three central dimensions, namely, environment, society and culture, and the economy, and includes 30 urban development indicators. Among Seoul's strategic priorities are reduction of Seoul's reliance on nuclear power, energy efficiency, and a sustainable energy action plan, as well as increasing female participation in economic activities. Previously, in 2013, the International Telecommunication Union issued a Smart Cities report devoted to Seoul's achievements. The Seoul Smart City programme includes a fast optical wire and wireless network; Seoul began distributing second-hand smart devices to low-income families, established a u-Seoul net in 2003, which connected major public buildings, offices and municipalities via fibre-optic cables arranged along Seoul's underground tunnels. The Smart Work Center was established to allow government employees to work closer to home, and 30% of staff were covered by this initiative in 2015. Seoul's open governance model implies a strong system of community mapping, through which citizens can raise concerns about their neighbourhoods and communities. Seoul's smart metering project aims to reduce electricity consumption by 10% and in 2012 a pilot project supplied 1000 families with smart meters. Addressing SDG goal 11, that is, ‘Sustainable cities and communities’, to make cities inclusive, safe, resilient and sustainable, the U-Seoul safety service was established to assist vulnerable groups such as the elderly, children and people with Alzheimer's: when the holder leaves the safety zone or pushes the emergency button, an alert is sent to police, guardians, fire departments and CCTV control centres. The administrative information is made available to citizens through the Open Governance 2.0 programme. The Open Data Square covers information on general administrative work, welfare, culture and tourism, city management, environment, safety, education, health, industry, economy and transportation. Smart solutions are used in Seoul to optimize the personal travel of citizens, planning routes, choosing green transport solutions, and reducing carbon emissions.

Seoul's metropolitan area maintained a significant share of the Korean economy, approaching 50% in 2013; at the same time, the Seoul metropolitan area provided employment for 50% of the country's population. Seoul's unemployment rate of 2.3% in 2014 matched the level of regional leaders like Beijing and Singapore, but was lower than that of Tokyo. Unemployment in Seoul is comparable with that of Munich, but is lower than that in Stockholm and San Francisco. At the same time, Seoul has a considerably lower unemployment rate than Vienna, London, Berlin, New York, Boston and Washington. Seoul has a significant rate of residents with higher education (40.6%), which is slightly lower than Singapore, but higher than the regional centres Beijing, Hong Kong, Shanghai and Shenzhen, and also higher than similar levels in Berlin, Vienna and Rome. The reasonably low Gini index of 0.3 underlines the values of equality in Korean society, and is considerably lower than that of regional leaders like Singapore, Beijing and Hong Kong. Compared with other global cities, the Gini index of Seoul is similar to that of Canadian (Vancouver and Montreal) and European cities (Stockholm, Vienna, Amsterdam and Munich), while it is significantly lower than in New York and San Francisco, Paris, Moscow and London (the accuracy of the latter the authors find problematic due to the high number of super rich individuals who own property in London and reside there for part of the year). Inflation in Seoul is low at 0.71%, which is comparable only to Copenhagen, not mentioning deflation in Stockholm. Compared with regional centres, Seoul's inflation is lower than Beijing, Singapore, Shanghai and Hong Kong. The cities with low inflation rates like Toronto, New York, Berlin and Munich exhibit higher rates of inflation than Seoul, to say nothing about other European cities such as Vienna, Amsterdam and London, and cities with high levels of inflation like Moscow and St Petersburg.

According to our model, which uses the Smart and Sustainable Urban Development Indicator Framework, the number of patents registered per 1000 inhabitants in Seoul is at a very respectable level of 1.4 per year. This is higher than the levels of the regional centres Shanghai, Hong Kong, Singapore and Beijing, but lower than the innovation powerhouses of Tokyo, Shenzhen and Taipei. Compared with European cities, it is higher than Vienna, London, Barcelona, Amsterdam and Berlin, but lower than European leaders Munich, Copenhagen and Stockholm. In North America, Seoul outperforms Montreal, Washington, Vancouver and New York, and follows the global leaders of Boston and San Francisco.

In the environmental field, CO_2 emissions per capita measured in Seoul on an annual basis at 4.5 are lower than the regional leaders Tokyo, Hong Kong, Singapore, Beijing, Shanghai and Shenzhen. Compared with European cities, Seoul is dominated by Scandinavian cities that traditionally exhibit very high performances (Stockholm and Copenhagen), but performs better than Paris, Amsterdam, Berlin, London, Vienna and Munich. Seoul also outperforms San Francisco, New York, Montreal, Boston, Washington and Los Angeles.

Seoul is characterized by very low water consumption per capita of 69.10 m^3/person per year, which compares favourably with Beijing, Shanghai, Shenzhen, Singapore, Tokyo and Hong Kong. Copenhagen, London and St Petersburg outperform Seoul; however, Stockholm, Paris, Moscow, New York, Washington and Los Angeles perform more poorly than Seoul.

In the sphere of waste management, Seoul generates 226.4 kg of municipal solid waste per person per year, which is less than Tokyo, Shanghai, Singapore, Beijing, Hong Kong and Shenzhen. Seoul compares favourably with Copenhagen, Amsterdam, Berlin, London, Paris, Stockholm and Vienna. In the USA, Seoul outperforms Washington DC, New York and Los Angeles. San Francisco is one of the few cities which generates less municipal solid waste than Seoul.

Recycling is definitely one of Seoul's main strengths, with 63.5% of all collected municipal solid waste being recycled. In this regard, Seoul outperforms the regional centres, Singapore, Tokyo, Hong Kong and Beijing. European cities (Vienna, London, Berlin, Munich and Amsterdam) perform poorer than Seoul on recycling. In the USA, Seoul performs better than New York but poorer than Los Angeles and San Francisco.

Green space in Seoul is not particularly abundant at 1.39 m^2/ per person, which is lower than Tokyo, Beijing, Shanghai, Barcelona, London, Paris, Stockholm, Berlin, Rome and Copenhagen.

6 | CONCLUSION

In this article we focused on global cities, the centres of economic activity, which are responsible for a considerable share of global CO_2 emissions and produce substantial volumes of waste. The application of multi-criteria analysis allowed us to produce a multidimensional ranking of 57 of the world's cities on 20 sustainability criteria. At the same time, various indicator weightings produced aggregate performance scores for global cities under four policy priorities: economic, social, environmental and smart city. The assessment identified sustainability leaders, namely, San Francisco, Stockholm and Seoul, and those cities that are lagging behind, namely, Johannesburg, Nairobi, Delhi, Mumbai, Almaty and Buenos Aires. It is important to note that there is no absolute global leader which outperforms all other cities in all dimensions. San Francisco dominates the global rankings in economic and environmental criteria, Stockholm in social and smart priorities. These results have put the performance of individual cities within the global context and presented the indicator-based sustainable development performance of individual cities within a coherent framework of multi-criteria decision aids. Learning from best practice and the worst cases in this context provides an invaluable insight for policy reform to create smarter, greener, more compact, socially diverse, economically strong and less polluting cities around the world.

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REFERENCES

Ahvenniemi, H., Huovila, A., Pinto-Seppä, I., & Airaksinen, M. (2017). What are the differences between sustainable and smart cities? *Cities*, *60*, 234–245.

Bithas, K. P., & Christofakis, M. (2006). Environmentally Sustainable Cities. Critical Review and Operational Conditions. *Sustainable Development*, *14*, 177–189.

Bolund, P., & Hunhammar, S. (1999). Ecosystem Services in Urban Areas. *Ecological Economics*, *29*, 293–301.

Brookings Institution. (2015). Global Metro Monitor 2014, Washington DC. https://www.brookings.edu/wp-content/uploads/2015/01/bmpp_gmm_final.pdf

Carbon Disclosure Project. (2018). https://www.cdp.net/en/cities

City of New York. (2012). Inventory of New York City Greenhouse Gas Emissions.

City of Rio de Janeiro. (2011). Greenhouse Gas Inventory and Emissions Scenarios of Rio de Janeiro, Brazil.

Dassen, T., Kunseler, E., & van Kessenich, L. M. (2013). The sustainable city: an Analytical-Deliberative Approach to Assess Policy in the Context of Sustainable Urban Development. *Sustainable Development*, *21*, 193–205.

European Commission. (2009). In European Commission (Ed.), *Sustainable Development Indicators. Overview of relevant Framework Programme funded research and identification of further needs in view of EU and international activities*. Brussels, Belgium.

Eurostat. (2016). Urban Europe. Statistics on cities, towns and suburbs. Retrieved from http://ec.europa.eu/eurostat/web/products-statistical-books/-/KS-01-16-691

García-Fuentes, M. Á., Quijano, A., De Torre, C., García, R., Compere, P., Degard, C., & Tomé, I. (2017). European Cities Characterization as Basis towards the Replication of a Smart and Sustainable Urban Regeneration Model. *Energy Procedia*, *111*, 836–845.

Girardet, H. (1993). *The Gaia Atlas of Cities: New Directions for Sustainable Urban Living*. London, UK: Gaia Books Ltd.

Girardet, H. (2004). *Cities People Planet: Liveable Cities for a Sustainable World*. New York, USA: John Wiley & Sons.

Girardet, H. (2014). *Creating Regenerative Cities*. London, UK: Routledge.

Girardet, H., & Mendonca, M. (2009). A Renewable World. Energy, Ecology, Equality. A Report to the World Future Council.

Girardi, P., & Temporelli, A. (2017). Smartainability: A Methodology for Assessing the Sustainability of the Smart City. *Energy Procedia*, *111*, 810–816.

GLA. (2016a). The Future of Smart: Harnessing digital innovation to make London the best city in the world. Retrieved from https://www.london.gov.uk/sites/default/files/gla_smartlondon_report_web_4.pdf

GLA. (2016b). The London Plan. The Spatial Development Strategy for London Consolidated with Alterations Since 2011. https://www.london.gov.uk/sites/default/files/the_london_plan_2016_jan_2017_fix.pdf

Gomez-Baggethun, E., & Barton, D. N. (2013). Classifying and valuing ecosystem services for urban planning. *Ecological Economics*, *86*, 235–245.

Hall, P. (2014). *Good Cities, Better Lives: How Europe Discovered the Lost Art of Urbanism (Planning, History and Environment Series)*. London, UK: Routledge.

Hall, P., Buijs, S., Tan, W., & Tunas, D. (2010). *Megacities. Exploring a Sustainable Future*. The Netherlands: nai010.

Hall, P., & Pfeiffer, U. (2000). *Urban Future 21: A Global Agenda for Twenty-First Century Cities*. London, UK: Routledge.

Hara, M., Nagao, T., Hannoe, S., & Nakamura, J. (2016). New key performance indicators for a smart sustainable city. *Sustainability*, *8*, 206.

ISO (2014). ISO 37120:2014(en). Sustainable development of communities — Indicators for city services and quality of life.

Kierstead, J., & Leach, M. (2008). Bridging the Gaps between Theory and Practice: a Service Niche Approach to Urban Sustainability Indicators. *Sustainable Development*, *16*, 329–340.

Klopp, J. M., & Petretta, D. L. (2017). The urban sustainable development goal: Indicators, complexity and the politics of measuring cities. *Cities*, *63*, 92–97.

LSE Cities. (2013). *Going Green: How cities are leading the next economy. A global survey and case studies of cities building the green economy*. London, UK: LSE.

Mairie de Paris. (2011). Le Bilan Carbone de Paris. In *Bilan des émissions de gaz à effet de serre*. Paris.

Manitiu, D. N., & Pedrini, G. (2016). Urban smartness and sustainability in Europe. An ex ante assessment of environmental, social and cultural domains. *European Planning Studies*, *24*, 1766–1787.

Martin, N., & Rice, J. (2014). Sustainable Development Pathways: Determining Socially Constructed Visions for Cities. *Sustainable Development*, *22*, 391–403.

Mayor of London. (2014). World Cities Culture Report.

Michael, F. L., Noor, Z. Z., & Figueroa, M. J. (2014). Review of urban sustainability indicators assessment. Case study between Asian countries. *Habitat International*, *44*, 491–500.

Monfaredzadeh, T., & Berardi, U. (2015). Beneath the smart city: Dichotomy between sustainability and competitiveness. *International Journal of Sustainable Building Technology and Urban Development*, *6*, 140–156.

Mori, K., & Yamashita, T. (2015). Methodological framework of sustainability assessment in City Sustainability Index (CSI): A concept of constraint and maximisation indicators. *Habitat International*, *45*, 10–14.

Naess, P. (1995). Central Dimensions in a Sustainable Urban Development. *Sustainable Development*, *3*, 120–129.

Pierce, P., Ricciardi, F., & Zardini, A. (2017). Smart cities as organizational fields: A framework for mapping sustainability-enabling configurations. *Sustainability*, *9*, 1506.

Quah, E. T. E. (Ed.) (2016). *Singapore 2065. Leading insights on Economy and Environment from 50 Singapore Icons and Beyond*. Singapore: World Scientific Publishing.

Rio de Janeiro. (2016). Resilience Strategy of the City of Rio de Janeiro, 100 Resilient Cities, Rockefeller Foundation. https://www.100resilientcities.org/wp content/uploads/2017/07/estra_res_rio_ingles_2.pdf

Roy, B. (1996). *Multicriteria Methodology for Decision Aiding*. Dordrecht, Boston, London: Kluwer Academic Publishers.

San Francisco Department for the Environment. (2016). Strategic Plan of San Francisco. https://plan.sfenvironment.org/

Seoul Metropolitan Government. (2016). Urban Planning of Seoul. https://seoulsolution.kr/sites/default/files/gettoknowus/%5BBrochure_En%5D%20Urban%20Planning%20of%20Seoul_2016.pdf

Shen, L., & Zhou, J. (2014). Examining the effectiveness of indicators for guiding sustainable urbanization in China. *Habitat International*, *44*, 111–120.

Shen, L.-Y., Ochoa, J. J., Shah, M. N., & Zhang, X. (2011). The application of urban sustainability indicators: A comparison between various practices. *Habitat International*, *35*, 17–29.

Shmelev, S. (2012). *Ecological economics: sustainability in practice*. Dordrecht, New York: Springer.

Shmelev, S. (2017a). Multidimensional Sustainability Assessment for Megacities. In S. Shmelev (Ed.), *Green Economy Reader. Lectures in Ecological Economics and Sustainability* (pp. 205–236). Dordrecht, New York: Springer.

Shmelev, S. (Ed.) (2017b). *Green Economy Reader. Lectures in Ecological Economics and Sustainability*. Dordrecht, New York: Springer.

Shmelev, S. E. (2011). Dynamic sustainability assessment: The case of Russia in the period of transition (1985–2008). *Ecological Economics*, *70*(11), 2039–2049.

Shmelev, S. E., & Shmeleva, I. A. (2009). Sustainable cities: problems of integrated interdisciplinary research. *International Journal of Sustainable Development*, *12*, 4–23.

Shmelev, S. E., & Shmeleva, I. A. (Eds.) (2012). *Sustainability Analysis: an Interdisciplinary Approach*. London, UK: Palgrave.

Shmelev, S. E., & Speck, S. U. (2018). Green Fiscal Reform in Sweden: Econometric Assessment of the Carbon and Energy Taxation Scheme. *Renewable & Sustainable Energy Reviews* (in press), *90*, 969–981.

Siemens. (2009). *European Green City Index. Assessing the environmental impact of Europe's major cities*. London, UK: Siemens.

Singapore. (2017). Sustainable Singapore Blueprint, Ministry of the Environment and Water Resources. https://www.mewr.gov.sg/docs/default-source/module/ssb-publications/41f1d882-73f6-4a4a-964b-6c67091a0fe2.pdf

Spangenberg, J. H. (2002a). Environmental space and the prism of sustainability: frameworks for indicators measuring sustainable development. *Ecological Indicators*, *2*, 295–309.

Spangenberg, J. H. (2002b). Institutional Sustainability Indicators: an Analysis of the Institutions in Agenda 21 and a draft set of indicators for monitoring their effectivity. *Sustainable Development*, *10*, 103–115.

Spangenberg, J. H. (2005). Economic sustainability of the economy: concepts and indicators. *International Journal of Sustainable Development*, *8*, 47–64.

Spangenberg, J. H. (2017). Hot Air or Comprehensive Progress? A Critical Assessment of the SDGs. *Sustainable Development*, *25*, 311–321.

Spangenberg, J. H., & Settele, J. (2010). Precisely incorrect? Monetising the value of ecosystem services. *Ecological Complexity*, *7*, 327–337.

UN. (2007). *Indicators of Sustainable Development: Guidelines and Methodologies*. New York: UN.

UN. (2015a). Technical report by the Bureau of the United Nations Statistical Commission (UNSC) on the process of the development of an indicator framework for the goals and targets of the post-2015 development agenda (working draft).

UN. (2015b). Transforming our world: the 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly on 25 September 2015, A/RES/70/1.

UN ECOSOC. (2015). The UNECE–ITU Smart Sustainable Cities Indicators. Retrieved from http://www.unece.org/fileadmin/DAM/hlm/documents/2015/ECE_HBP_2015_4.en.pdf

UN HABITAT. (2013). Planning and Design for Sustainable Urban Mobility: Global Report on Human Settlements.

UN HABITAT. (2016). Urbanisation and Development. Emerging Futures.

UNECE. (2013). Framework and suggested indicators to measure sustainable development. Prepared by the Joint UNECE/Eurostat/OECD Task Force on Measuring Sustainable Development 27 May 2013.

UNECE, & ITU. (2016). Rome Declaration Adopted by the participants of the Forum “Shaping smarter and more sustainable cities: striving for sustainable development goals”, on 19 May 2016 in Rome. Retrieved from https://www.itu.int/en/ITU-T/Workshops-and-Seminars/Documents/Forum-on-SSC-UNECE-ITU-18-19-May-2016/Rome-Declaration-19May2016.pdf

UNEP. (2011). *Towards a Green Economy. Pathways to Sustainable Development and Poverty Eradication*. Nairobi: UNEP.

Valentin, A., & Spangenberg, J. H. (2000). A guide to community sustainability indicators. *Environmental Impact Assessment Review*, *20*, 381–392.

Wei, Y., Huang, C., Lam, P. T. I., & Yuan, Z. (2015). Sustainable urban development: A review on urban carrying capacity assessment. *Habitat International*, *46*, 64–71.

Wei, Y., Huang, C., Li, J., & Xie, L. (2016). An evaluation model for urban carrying capacity: A case study of China's mega-cities. *Habitat International*, *53*, 87–96.

WHO. (2016). Ambient air pollution: A global assessment of exposure and burden of disease.

Wong, C. (2015). A framework for ‘City Prosperity Index’: Linking indicators, analysis and policy. *Habitat International*, *45*, 3–9.

World Bank. (2013). Building Sustainability in an Urbanizing World. A Partnership Report.

Yigitcanlar, T., Dur, F., & Dizdaroglu, D. (2015). Towards prosperous sustainable cities: A multiscalar urban sustainability assessment approach. *Habitat International*, *45*, 36–46.

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