Global Urban Sustainability Assessment: A Multidimensional Approach

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Abstract. This paper examines a database of over 140 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. It builds a comprehensive global CO_2 emissions model explaining 80% of the variance in urban CO_2 emissions across the globe. The results point towards a range of important variables capable of characterising urban CO_2 emissions: share of coal energy in the electricity mix, share of renewables, recycling rates, travel patterns and so on. Examples of the three leading cities, San Francisco, Stockholm and Seoul are discussed from the point of view of policies and performance. The 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: multi-criteria decision aid, sustainable cities; indicators; sustainable development; environmental policy; smart city

1. Introduction

UNEP Green Economy Report highlighted urban sustainability as one of its important dimensions (UNEP 2011). This topic receives a lot of attention in the EU, USA and increasingly China and Latin America since the Rio Summit of 1992, the Rio+20 Summit in 2012 and, especially, in the 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 (UN Habitat, 2016). SDG 11 'Sustainable Cities and Communities' aims to 'make cites and human settlements inclusive, safe, resilient and sustainable' (UN, 2015b). UNECE and ITU have launched a new United for Smart and Sustainable Cities initiative in 2016.

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

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

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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, environmental as well as cultural aspects (UN ECOSOC, 2015).

Cities are contributing a significant share of global CO2 emissions (75%) and will experience tangible effect from its consequences. Bai et al. (2018) asserts that by 2030 millions of people and US$4 trillion of assets will be at risk from climate-change-induced extreme events. Founded in London in 2005 at the summit of representatives of 18 leading megacities, the C40 partnership currently numbers 89 cities from over 50 different countries aimed at taking action against climate change. ICLEI, Local Governments for Sustainability is uniting over 1500 cities towns and regions to build a sustainable future.

In this article we start by exploring a large database of over 140 global cities and search for meaningful relationships between various indicators in the global dataset. We then build a cross-sectional linear regression model, linking urban CO_2 emissions and various external, infrastructure, policy, behaviour and technology variables. The article concludes with a description of sustainability strategies and policies adopted in the leading cities of the world, which could help us to understand its success. The article is organized as follows. Section 1 offers an introduction to the topic. Section 2 discusses data and indicators used. Section 3 presents the results of regression analysis of linkages among sustainability indicators. Section 4 discusses the application of cross-sectional linear regression model for CO_2 to 71 global cities. Section 5 explores the sustainability strategies and policies in the most sustainable cities identified in our research. Section 6 concludes.

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 (EC, 2009), a Sustainable Development Indicators Frameworks (UNECE, 2013), a new ISO 37120 standards on Sustainable Development of Communities (ISO, 2014), a Sustainable Development Goals framework (UN, 2015), a Smart Sustainable City Indicator Framework (UN ECOSOC, 2015). These frameworks are discussed extensively in a range of comparative reviews: (Valentin & Spangenberg, 2000), Spangenberg (2002a,b), Spangenberg (2005), Kierstead and Leach (2008), Monfaredzadeh & Berardi (2015), Hara et al (2016), Manitiu & Pedrini (2016), Ahvenniemi et al (2017), Garcia-Fuentes et al (2017), Girardi & Temporelli (2017), Spangenberg (2017), Klopp & Petretta (2017) and Pierce et al (2017).

Recently there has been a growth of interest in indicator-based sustainability assessments for cities: (Shen and Zhou, 2014), (Mori and Yamashita, 2015), (Wong, 2015), (Yigitcanlar et al, 2015), (Wei et al, 2015), (Wei et al, 2016). The indicators following the International Urban Sustainability Indicators List proposed in (Shen, 2011) include the 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 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 and UNECE-ITU Smart Sustainable City Indicators) has shown a difference in focus, balance between economic, social and environment dimensions and 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. On the contrary, the UNECE-ITU Smart Sustainable Cities Indicator framework is more balanced between different dimensions of sustainability and formulated with a lot of clarity and a forward-looking strategic vision in mind.

Selection of individual indicators for cities, chosen for the present paper, was based on an earlier sustainable cities framework (Shmelev and Shmeleva, 2009), inspired by our dynamic sustainability assessments carried out for countries (Shmelev, 2011, 2015) and adapted for the urban scale Shmelev (2017). 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 PPP, 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, 2017), identifying redundant variables and adding relevant dimensions, the set of criteria took its final shape numbering twenty criteria as a result of several iterations.

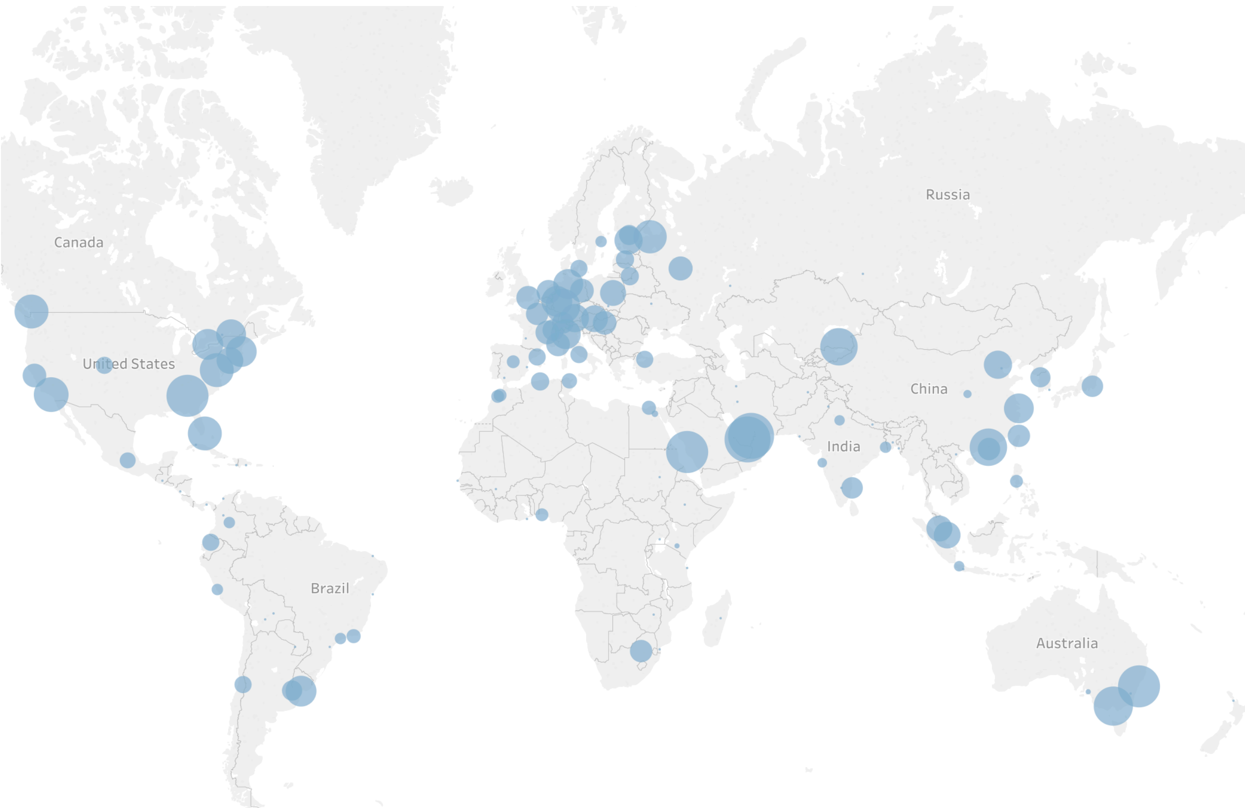

Figure 1. CO_2 emissions. Source: Environment Europe™ Sustainable Cities Database, http://environmenteurope.org/, 143 global cities, 2018

The Environment Europe™ Sustainable Cities database includes 143 cities in Europe, North America, South America, Africa, Asia, and Oceania. Our study draws on a wide range of sources from Eurostat (2016), city governments, UN Habitat, World Bank, CDP, Bloomberg. As a matter of example, we would like to illustrate the geographical spread of the Environment Europe database with CO_2 emissions data (Fig 1). CO_2 emissions are very high in Melbourne and Sydney, Dubai and Doha, Miami, Shanghai, Almaty and much lower in Stockholm, San Francisco, New York, Tokyo, Rio de Janeiro, Paris and Madrid.

3. Cross-Section Regression analysis

Our goal in this section was to test several hypotheses regarding the inter-disciplinary links among urban sustainability dimensions. The hypotheses were derived from the assertion in the UN Guidelines on Sustainable Development Indicators (UN, 2007), which emphasised the interdisciplinary connections between sustainable development indicators. The exact formulation of the hypotheses is based on our previous research outlined in Shmelev and Shmeleva (2009), Shmelev (2017) and Shmelev and Speck (2018).

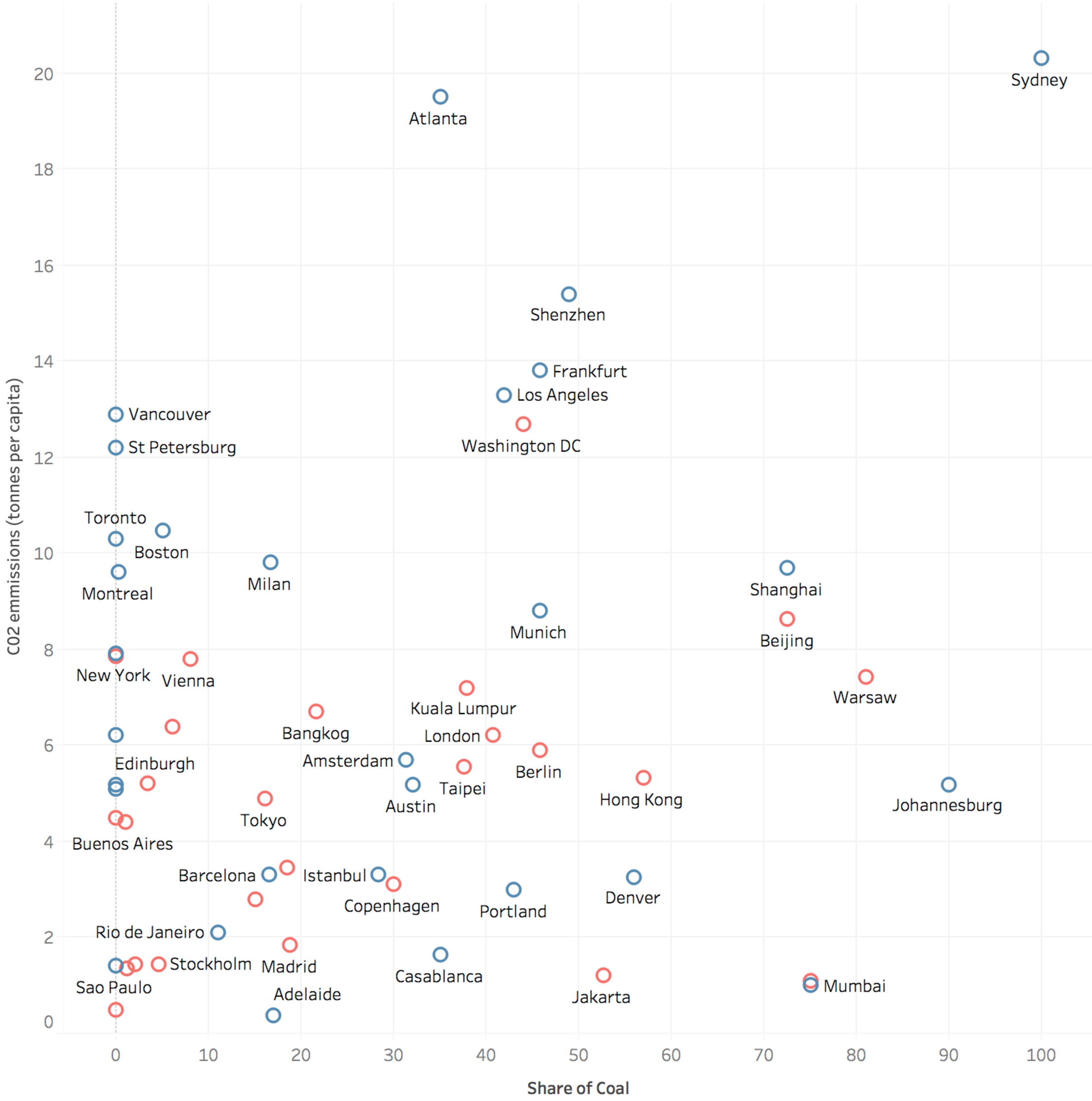

Figure 2. Correlation between CO_2 emissions and the share of coal in the energy mix for global cities. Source: Environment Europe™ Sustainable Cities Database, 2018.

The confirmation of our hypothesis of a highly significant correlation between the amount of CO_2 emissions and the share of coal, the most carbon-intensive technology at present in the energy mix (Figure 2), reinforces the need for an urgent transformation and decarbonisation of the energy sector. Such cities as Sydney, Warsaw, Hong Kong, Denver, Portland, Los Angeles, Washington, Shenzhen have above-average levels of coal in the energy mix and exhibit high per capita CO_2 emission. On the other hand such cities as Sao Paolo, Rio de Janeiro, Bogota, Quito, Madrid, Adelaide, Copenhagen, Rome have relatively low share of coal in the energy mix and lower levels of CO_2 emissions per capita.

A significant correlation between CO_2 emissions and the share of trips made by walking, cycling and public transport has been confirmed (Figure 3), which enriches our understanding of this wonderful urban planning tool for improving air quality and making the cities greener.

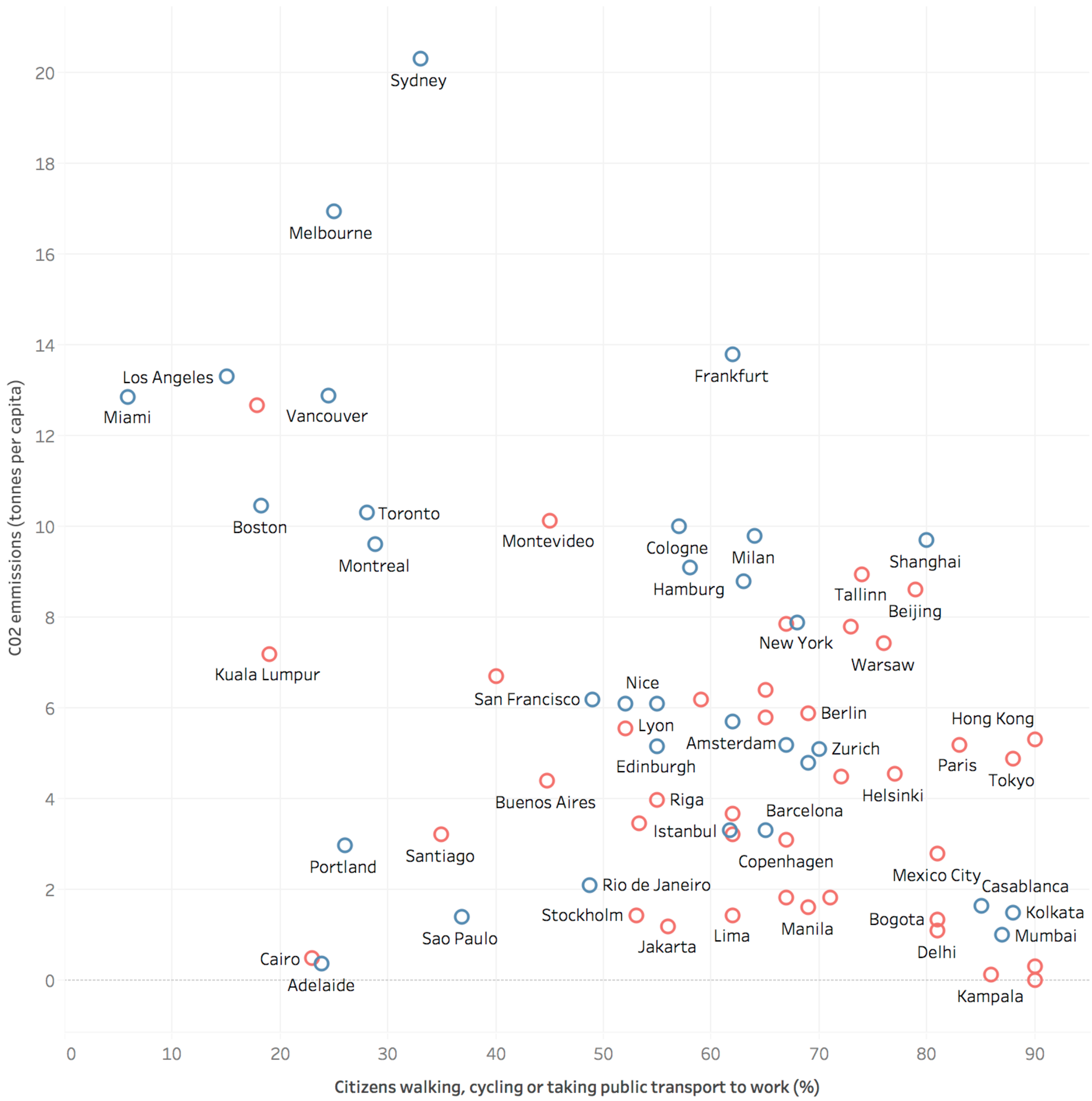

Figure 3. Correlation between CO_2 emissions and the share of trips made by walking, cycling and taking public transport. Source: Environment Europe™ Sustainable Cities Database, 2018

Such cities as Stockholm, Mumbai, Bogota, Delhi, Mexico city, Paris, Amsterdam, Seoul, Barcelona, Sao Paolo, Berlin, Singapore, 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, such cities as Sydney, Shenzhen, Almaty, Los Angeles, Miami, Kuala Lumpur, Boston, Vancouver, 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 4). This clearly reinstates the tendency in such cities like Sao Paolo, Bogota, Montreal, Stockholm, Rio de Janeiro, Zurich and Copenhagen that are largely powered by hydro energy to 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, Shenzhen that tend to have lower levels of renewables in the energy mix, tend to exhibit higher per capita CO_2 emissions.

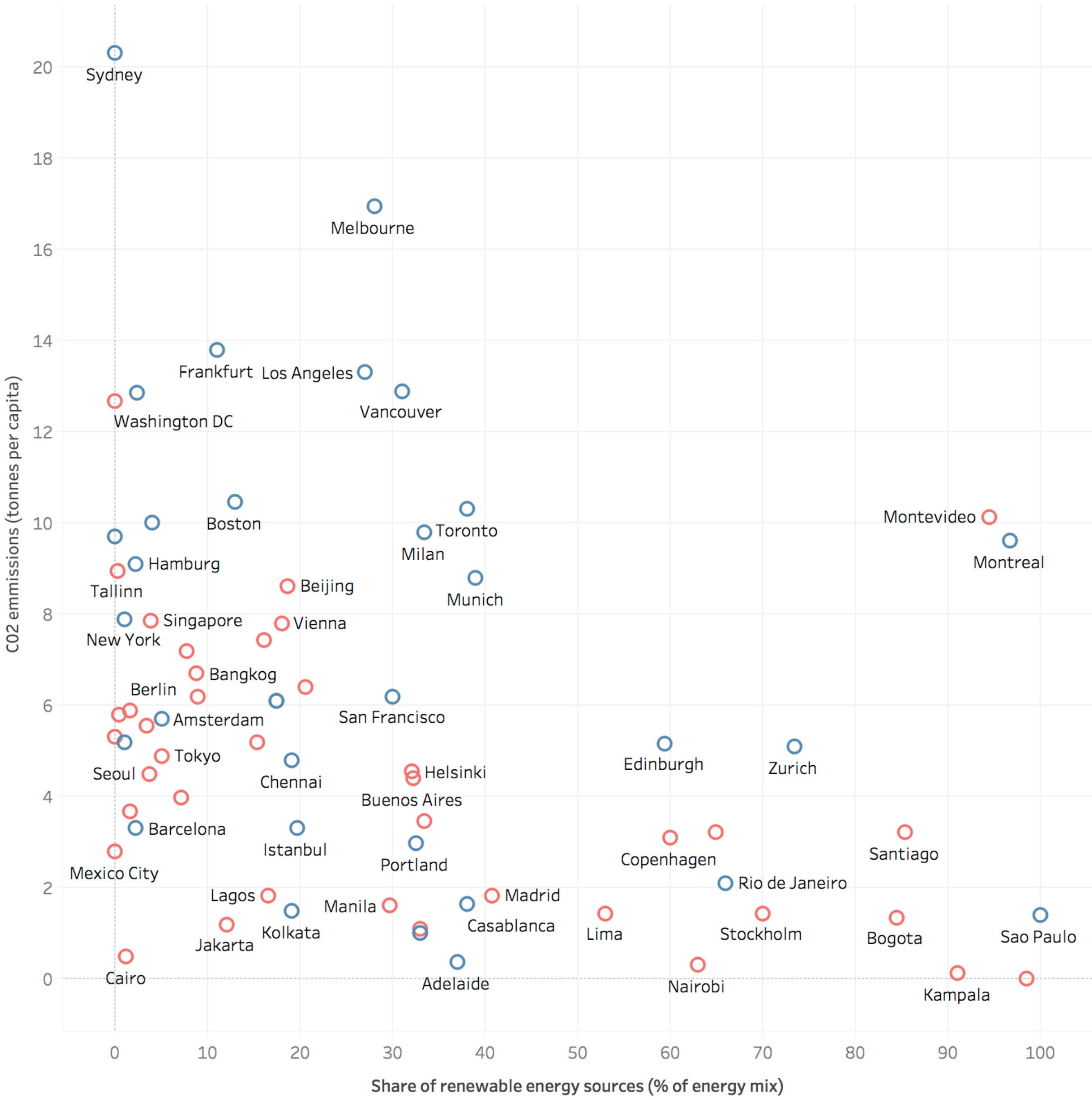

Figure 4. Correlation between CO_2 emissions and the share of the renewable energy for global cities. Source: Environment Europe™ Sustainable Cities Database, 2018

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 phenomenon and shows cities like Los Angeles, Almaty, Atlanta, Miami, Toronto, 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, Rome exhibit lower levels of per capita CO_2 emissions accompanied by lower water consumption.

The research outlined above forms an important step in creating multivariate regression models explaining variation in key urban sustainability indicators, such as CO_2.

4. Urban CO_2 function

Based on the global data covering 71 cities, contained in the Environment Europe Cities Database we were able to generate a regression that captured 80% of the variation in urban CO_2 emissions across the whole world (Figure 5). Urban CO_2 emissions tend to decrease with the increasing daily mean temperatures in the city (Table 2). On average, higher temperatures result in reduced need for heating and associated CO_2 emissions. At the moment, we cannot take into the account increased electricity consumption due to air conditioning. Cities with an OECD capital status tend to exhibit significantly lower CO_2 emissions possibly as a result of higher technological development in public transport systems, electric cars and pedestrianisation as a new trend in urban planning and design.

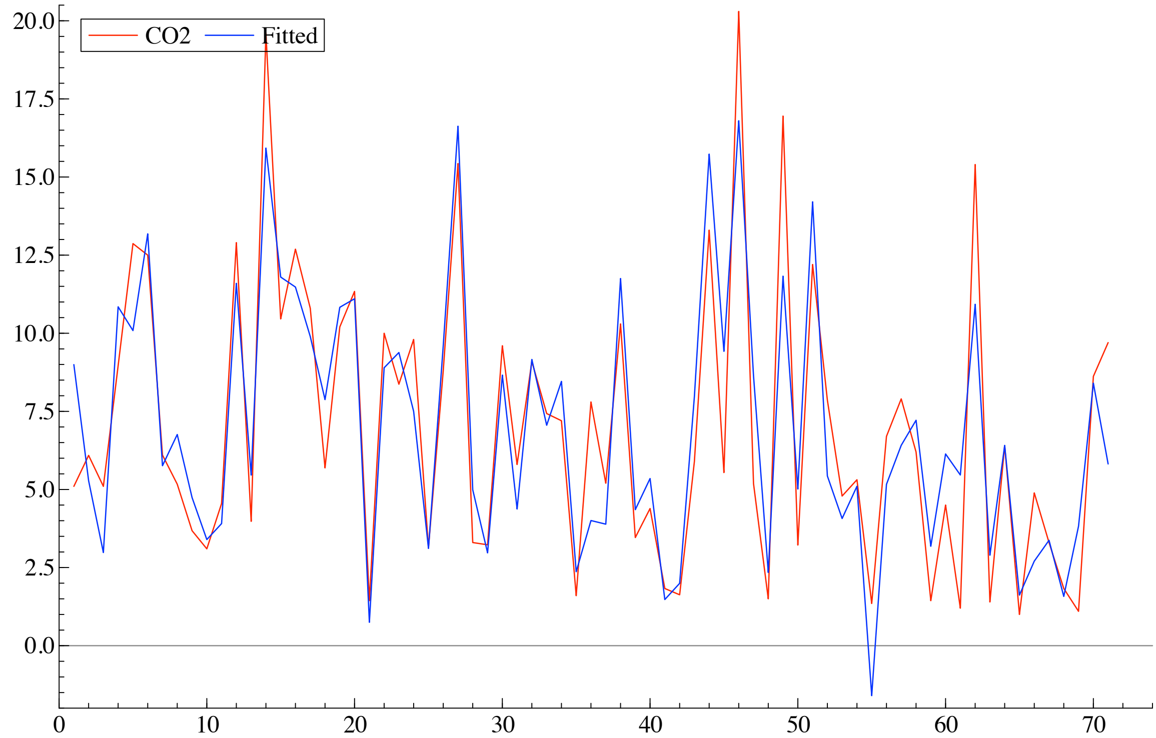

Figure 5. Global Urban CO_2 Emissions Linear Regression, (Environment Europe™ Cities Database, 2014 data).

The large share of renewables in the energy mix tends to reduce urban CO_2 emissions according to our results. On the other hand, the share of coal in the energy mix tends to increase urban CO_2 emissions. And additional behavioural variable, representing the share of trips made by walking, cycling and using public transport is shown to reduce urban CO_2 emissions (Table 1), which compared to petrol-based combustion engine cars generate less harmful GHGs. Paradoxically, higher recycling rates under every else being equal, tend to increase CO_2 emissions as additional amounts of energy are need for complex recycling (statistical significance of this factor is lower, but is it still significant at 10%). The next variable, CO_2 tax is reflecting the existing structure of incentives globally and shows an effect to reduce CO_2 emissions, however statistical significance of this factor is lower.

Table 1. CO_2 regression coefficients in the linear urban regression

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	-0.0376761	0.01115	-3.38	0.0013	0.1534

Energy Mix					
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

Source: Environment Europe Cities Database, 71 observations, R^2=0.805394

Overall, this equation 'explains' 80% of the variance in the global CO_2 emissions. Such model can be used for out-of-sample forecasting.

5. Most sustainable global cities

Below we will explore some of the most sustainable and smart cities globally trying to explain how they achieved their remarkable success, paying particular attention to climate-related issues. Among the most successful cities are San Francisco, the US high tech and sustainability hub in the most economically successful state of the US, California, which is equivalent to the economy of France in size, as well as two national capitals: Stockholm and Seoul (Figure 6), which stems from our previous research in sustainability benchmarking.

San Francisco

San Francisco leads our ranking in Economic and Environmental Dimensions worldwide, which corresponds to the World Economic Forum ranking. 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: 1) Promoting Healthy Communities and Ecosystems; 2) Leading on Climate Action; 3) Strengthening Community Resilience; 4) Eliminating Waste; 5) Amplifying Community Action.

In particular, Goal 2 uses an active target to reduce greenhouse gas emissions by 40% by 2025 and has the following 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 shift to 100% renewable grid electricity by 2030 and maximize local on-site generation of renewable electricity through policy development and investment; decarbonize the transport sector by facilitating deployment of electric and zero-emissions vehicles.

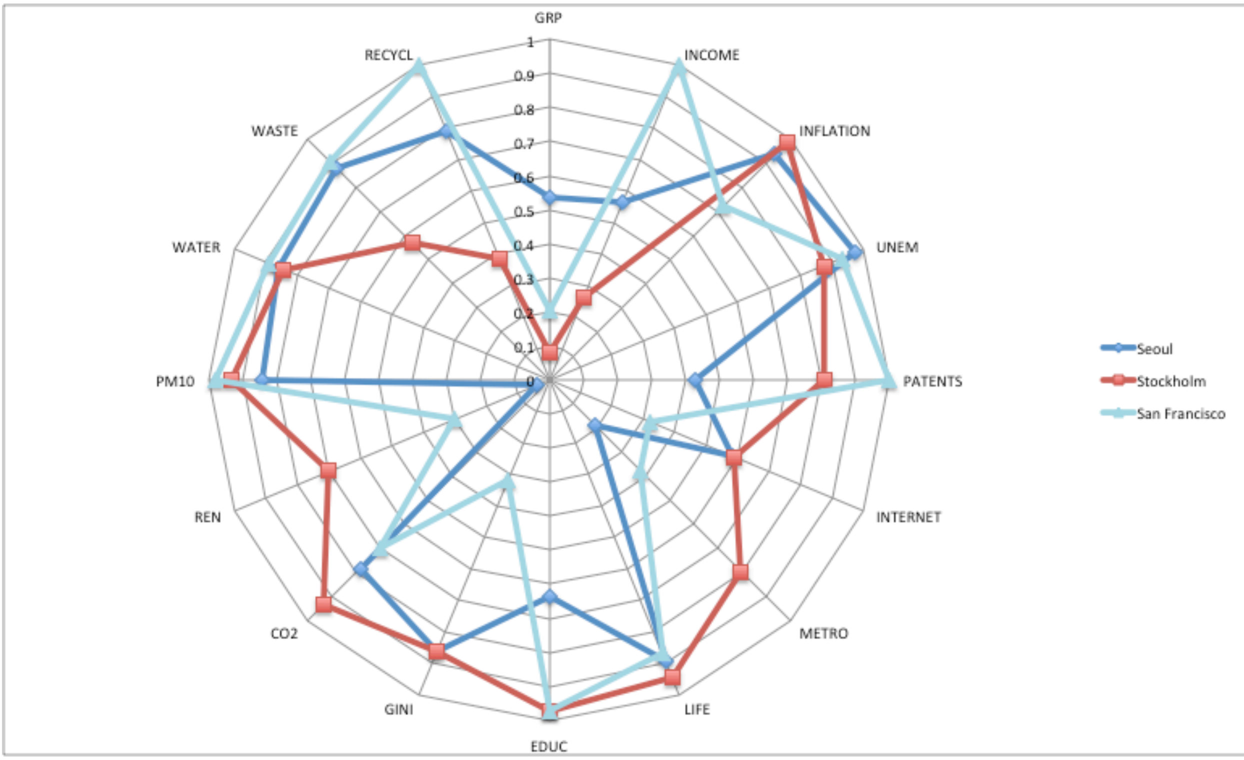

Figure 6. Comparison of the most successful cities globally: San Francisco, Stockholm, Seoul. Further away means better performance on each of the indicators.

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). 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 $\mu g/m^3$, which is within WHO limit of $20 \mu g/m^3$. It has a reasonably diverse systems of underground public transport.

Economically, San Francisco is one the most vibrant places in the world. With high per capita income of 88518 USD at PPP in 2010 prices, inflation is low at 3.8%, unemployment at 4.4%, which is three times lower than 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 relatively high income inequality could limit San Franciso's performance in the social dimension.

Stockholm

Stockholm has received a prestigious prize of a 'European Green Capital' in 2010. The city of Stockholm adopted Environmental Program for 2016-2019, based on complementarity between environmental protection and human needs. The six priority areas of this programme include: sustainable energy use, environmentally friendly transport; sustainable land and water use, resource efficient recycling, a non-toxic Stockholm, 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 approximately 4.7% of GDP in foreign direct investment per annum. At the same time, it invests in the range of 3.7% of GDP in research in development, which 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 modernisation 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.

The Stockholm economy is largely innovations-based with the number of new patents registered (2.62 per 1000 inhabitants) higher that all other regional European centres including technological giants like Copenhagen, Munich, Zurich. Stockholm outperforms Tokyo. At the same time Stockholm is characterised by very low inflation, in fact deflation at 0.04%. The level of higher education in Stockholm is 58% of all the residents aged 25-64. Stockholm, representing the Nordic governance model, is characterized by high level of taxation as % of GDP and a reasonably low Gini index of income inequality (0.3).

In the environmental dimension Stockholm is characterized by low CO_2 emissions at 1.44 t per capita. 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 the share of renewables in the energy mix (70%), following Zurich. Stockholm's performance on renewables is considerably better than other European cities – Copenhagen, Edinburgh, Madrid, Rome, Moscow, Vienna, Paris, London, Amsterdam. On the other hand, according to the data on the share of all trips made by walking, cycling and using public transport, Stockholm is unfortunately not in the lead, following Vienna, Madrid, Moscow, Amsterdam and London at a modest level of 53%.

Another important parameter for 'explaining' low CO_2 emission levels is infrastructure, which gives affordance to use public transport by residents. In this regard Stockholm is characterized by a highly diversified system of underground networks with 108 underground stations per 100.000 inhabitants. This is better than most European cities: Madrid, Amsterdam, London, Rome, Berlin, except Paris. Air quality in Stockholm is at a good European level with an average annual concentration of PM_{10} at 26μg/m^3, which is nevertheless higher than the maximum recommended by the World Health Organization of 20μg/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 the field of circular economy, Stockholm generates rather large amounts of municipal solid waste of 597 kg/person per year, 31% of which is recycled. Other European cities practice less resource-intensive lifestyles: Madrid, Amsterdam, Berlin, London, Paris, Vienna. Recycling rates are lower than Stockholm in Madrid, Rome, Paris, Copenhagen, and higher in Vienna, London, Berlin and Amsterdam

Seoul

In November 2017 Metropolitan Government of Seoul adopted 17 Sustainable Development Goals and 96 targets. Seoul Plan 2030, and urban planning document, covers three central dimensions: 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 sustainable energy action plan, increasing female participation in economic activities. Already in 2013, the International Telecommunication

Union issued a Smart Cities report devoted to Seoul's achievements. The Seoul's Smart City programme includes 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 a fiber-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 could 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 covered 1000 families with smart meters. 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 personal travel of citizens, planning routes, choosing green transport solutions and reducing carbon emissions.

Seoul's metropolitan area maintained a significant share of Korean economy approaching 50% in 2013; at the same time Seoul metropolitan area provided employment for 50% of the country's population. Seoul's unemployment rate of 2.3% in 2014 was at the level of regional leaders like Beijing and Singapore, but lower than that of Tokyo. Seoul has a significant rate of residents with higher education (40.6), which is slightly lower than Singapore but higher than regional centres Beijing, Hong Kong, Shanghai, Shenzhen, and is 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, Hong Kong. Inflation in Seoul is low at 0.71%, which is comparable only to Copenhagen, not mentioning deflation in Stockholm. 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.

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

Recycling is definitely one of the main strengths of Seoul with 63.5% of all collected municipal solid waste being recycled. 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 for economic activity and the cities that are responsible for a considerable share in global CO_2 emissions and produce substantial volumes of waste. The application of cross-sectional regression allowed us to produce a robust CO_2 emission model for cities. The key factors affecting the CO_2 emissions for cities we identified are: the share of coal in the energy mix, share of renewables, share of trips made by walking, cycling and public transport, mean annual temperature, OECD capital status, recycling rates and CO_2 taxes. All the factors combined contribute to the 80% of the variation in urban CO_2 emissions worldwide. The multidimensional sustainability assessment identified sustainability leaders: San Francisco, Stockholm and Seoul. The 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. Learning from best practices and 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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