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Exploring the energy use drivers of 10 cities at microscale level

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Abstract

Cities are responsible for the predominant share of anthropogenic environmental pressures. Recently, consistent methodologies to measure the metabolism of cities have been developed in order to enhance comparability between case studies and enable cross-city comparisons at the macro-scale. This comparison illustrated potential factors and drivers explaining macro-scale differences between cities. However, such studies rely on very few data points and look at cities as homogenous entities omitting their complex functioning. When looking at the relationships between urban characteristics and metabolic flows at smaller spatial scales, drivers appear to be different than in macroscopic analyses, pointing towards the importance of taking microscale urban heterogeneity into account. The aim of this paper is to improve our understanding of these effects by analyzing the relationship between energy use and various urban indicators at a microscale level for ten cities (Brussels, Buenos Aires, Cape Town, Chicago, Glasgow, London, Los Angeles, Milan, New York City and San Francisco).

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1. Introduction

Cities host 54% of global population and are responsible for 60 - 80% of anthropogenic CO_2 emissions, as well as account for 75% of the global consumption of natural resources [1]. This share is likely to become even greater as cities are projected to host 80% of global population by 2050 [2]. Mitigation strategies at an urban scale are thus a *conditio sine qua non* to reach the Paris Agreement goals [3]. To develop pathways towards more sustainable cities, a good understanding of the drivers of the urban energy consumption is key [4]. Urban metabolism describes the resource and pollution flows entering and exiting cities, in order to analyse and monitor their quantities, relationship with the local context, hinterlands (global and regional), environmental impacts, etc. Numerous case studies have been carried out to assess these flows' quantities, their relationship to the local context and the global hinterland, and their environmental impact (for instance [5,6,7]), but their system boundaries, scope, methodology and outcomes differ, thus complicating cross-city comparison and the identification of macro-scale patterns. However, by identifying patterns in resource use in cities it becomes possible to bring forward their drivers and therefore propose and implement mitigation strategies. Recently, a lot of effort is being put in the creation of consistent methodologies to measure the urban metabolism in order to enhance comparability and push forward the identification of generalizable drivers of urban resource and energy consumption at an aggregate level [8,9,10,11]. These studies identify potential drivers by comparing the relationship between urban energy use at the city level and a number of other urban indicators across different cities. Cities are thus examined as homogeneous wholes and the developed relationship is built based on a relatively small sample - often only a handful of cities. In fact, the small size of the sample could imply that the relationship found is not accurate enough and that policies implemented based on these finding could lead to undesired effects. Through the advent of open data and big data, urban indicators and energy use data are increasingly available at a disaggregated urban scale [12], some studies have now started to look at correlations between these variables at smaller spatial scales, thus increasing the sample size and the accuracy of their relationship. However, such studies are still exceptions and only exist for a handful of cities [13, 14, 15].

The aim of this paper is to improve the understanding urban energy use drivers by performing cross-city comparisons at a micro-scale level. To do so, two main aspects will be covered. On the one hand, to address some of the issues encountered by previous studies, notably by significantly increasing the number of data points at the base of the energy use drivers identification. On the other hand, to capture additional effects by enabling the illustration of intra-urban behavior in energy consumption, and by separating city-specific factors from generalizable drivers such as affluence or economies of scale (source). For this, micro-scale urban energy use data from 10 cities - Brussels, Belgium; Buenos Aires, Argentina; Cape Town, South Africa; Chicago, USA; Glasgow, Scotland; London, United Kingdom; Los Angeles, USA; Milan, Italy; New York City, USA and San Francisco, USA - are correlated and analyzed with social urban indicators such as population, population density, and income. Energy use flows were disaggregated by different sources (electricity and natural gas) and different uses (residential and total use) to depict a multi-faceted relationships.

In the following section, we present the methodology adopted for data collection and analysis as well as the encountered challenges, followed by a presentation of the results both at the intra- and inter-city level, and a discussion thereof in relation to the added value of using micro-scale data for this type of analysis.

2. Data collection

Data collection was one of the most time-consuming tasks of this research. It involved searching for disaggregated energy use data for a number of global cities through open database platforms, national and local statistical offices, grid operators, private energy companies, and literature reviews [9], historical records and reports. Given that available data and data collection methods vary across countries, the data collection process had to be adapted to each city and ranged from the download of open access tables to carrying out specific requests to urban administrations and grid operators. This data collection process resulted in energy use data and socioeconomic and demographic indicators for 10 global cities.

When collecting energy use data, the major challenges laid in: the lack of supplementary information detailing the origin source of the data, what exactly they were encompassing, the main use of each energy source (heating, cooking, etc.) and whether there were any estimations to the data provided. In addition, while some cities provided energy use data both by source (electricity, natural gas, coal, fuel, or total) and demand sector (residential, commercial, industrial, agricultural, transport, or total), others only provided either one or the other. Unfortunately, this discrepancy in energy use data hinders a more extensive comparability of cities. For the analysis, only the energy flows with the largest overlap between the 10 cities were considered. As shown in Table 1, total electricity use was available in 7 cases, residential electricity use in 6 cases, and natural gas in 6 cases.

The gathered energy flows were complemented by a number of urban indicators corresponding to potential drivers of the urban energy demand. Collection of this data was less time consuming, since it was often readily available in the form of census data or at local statistical offices, which were sometimes linked to open data platforms. In fact, a wealth of indicators were available and collected, including demographics, socio-economic data, built environment statistics, etc. In the present paper, only population, population density and household income are considered, as they already allow to capture quite different phenomena (affluence effects, economies of scale, etc.) and were available for at least 9 of the studied cities. However, in some cases it proved to be difficult to find data on potential drivers for the same spatial units as the energy use data and for some cities even the census data was difficult to access.

Table 1. Socioeconomic, demographic and energy data for 10 selected global cities at macroscale level (N/A: Not Available)

Indicator	Milan	London	Brussels	Glasgow	NYC	LA	San Francisco	Chicago	Cape Town	Buenos Aires
HDD[1] (15.5/15.5)	1,840	1,781	2,080	2,410	1,958	306	754	2,785	485	740
CDD (15.5/15.5)	918	349	362	105	1,145	1,413	439	986	1,090	1,423
Population (million)	3.2	8.7	1.1	0.6	8.2	4.6	0.8	3.1	3.7	12.8
Area (km²)	1,574	1,572	161	172	775	1,835	121	1,477	2,461	3,209
Number of MTUs	134	33	19	133	236	123	27	68	82	25
Name of the MTUs	Communes	Boroughs	Municipalities	Intermediate zones	Zip codes	Zip codes	Zip codes	Zip codes	Wards	Partidos
Income $ PPP	29,782	76,399	35,277	16,667	N/A	58,820	75,813	55,437	18,461	N/A
Electricity (MWh)	61,247	40,957	5,004	1,279	N/A	N/A	1,412	11,610	N/A	34,170
Residential electricity (MWh)	24,292	13,204	2,226	1,113	N/A	60,662	N/A	N/A	5,060	10,921
Natural gas (MWh)	N/A	59,102	9,732	1,807	81,002	N/A	4,355	31,792	N/A	N/A

An important challenge that was encountered during data collection was that energy use and urban data were not necessarily at the same spatial scale or microterritorial unit (MTU). A number of iterations had to be carried out in order to enable the relationship between urban and energy data. In addition, to enhance the comparability of results between US cities, all data presented here were collected at ZIP code level. In fact, the ways in which cities are disaggregated into smaller spatial units varies a lot across the different cities, and oftentimes there are even significant differences between the city center, which is often considered as one unit, and the surrounding units, which are often much more disaggregated. This leads to issues regarding the comparability of the different cities and microscale spatial units. It is important to mention here, that in some cases the entire metropolitan area was considered (e.g. Milan, Cape Town, etc.) whereas is other cases only the central urban administration area was considered.

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[1] "*Heating degree days*", or "*HDD*", are a measure of how much (in degrees) and for how long (in days), outside air temperature was *lower* than 15.5°C and "*Cooling degree days*", or "*CDD*", are the same measure for outside air temperature *higher* than 15.5°C (http://www.degreedays.net/)

3. Data analysis: Understanding global city typologies

As it is visible through Table 1, the size of cities compared and the number of inhabitants of the cities compared are very different. In fact, there is a factor of 26 between San Francisco's and Buenos Aires' area whereas the highest difference in population is between Glasgow and Buenos Aires by a factor of 21. Nevertheless, Buenos Aires total electricity use comes at 3rd place (although data for NYC and LA are missing) and residential electricity use comes at 4th place (although data for NYC is missing). This difference in the order for each of these indicators, already highlights that their relationship is not obvious. As mentioned, current state of research of energy use drivers identification at macroscale generally ends at this stage. This research will detail the energy use of each city by the number of MTUs available. In other words, while at the macroscale the determination relationship between urban characteristics and energy use for this study would be based on a sample size of 10, at the microscale the sample size would be of 880 (the sum of all MTUs).

To identify potential drivers of energy use in cities, patterns in cities' energy consumption related to various socioeconomic and demographic indicators were analyzed. For this preliminary study, energy use (through residential electricity consumption, total electricity consumption and natural gas consumption), and as urban indicators (population, population density, and median household income) were crossed. Since for some cities only natural gas consumption data were available, while in others only the electricity consumption data were available, all cities could not be compared to each other (See Table 1).

To enable the analysis of both intra-city differences as well as inter-city differences, a correlation analysis between the different variables by looking at the disaggregated spatial units in each city individually was carried out. This procedure enables to examine whether relationships between these variables are similar across different cities, or whether different cities exhibit different behavioral patterns. In other words, whether urban energy policies are unique to urban contexts or can be transposed to a number of cities with different climatic, socio-economic and territorial characteristics.

4. Results

Figure 1 displays a matrix of 9 scatterplots for the different combinations of urban indicators and energy use indicators for each of the 10 cities, and thus illustrates the behavioral differences between these relationships across the different cities. Each scatterplot (in a log x log scale) provides a linear regression among these variables at micro-territorial-unit (MTU) level for each city. This enables to explore which energy use drivers are shared between MTUs across the different cities.

It is interesting to point out that even when looking at microscale correlations, the trends and patterns identified by Kennedy et al. (2015) in their macroscale analysis still seem to apply. In fact, most cities exhibit economies of scale effects, with per capita energy consumption decreasing in relation to increasing population density and population (column 1 and 3 of Figure 1, respectively), although Buenos Aires and some US American cities are outliers to this trend. In addition, the effect of affluence seems to be more clearly visible (column 2 of Figure 1), with microscale units' energy consumption generally increasing with affluence in all the cities.

However, these relationship are far less evident than at a macroscale and a high degree of heterogeneity seems to exist across the cities, as can be seen in Figure 1. There are even outliers to the general trends, for which the relationship between the urban indicators and urban energy use goes in the opposite direction as the one predicted by studies at the macro-scale level, such as for instance Buenos Aires and San Francisco.

Furthermore, even for the cases where the cities seem to be in alignment with the trends predicted by previous studies, the relationships vary significantly in intensity, and in some cases, are almost nil (slope of the regression line close to zero). There thus seem to be other important elements playing into energy consumption, which differ between these cities and the European cities and Cape Town.

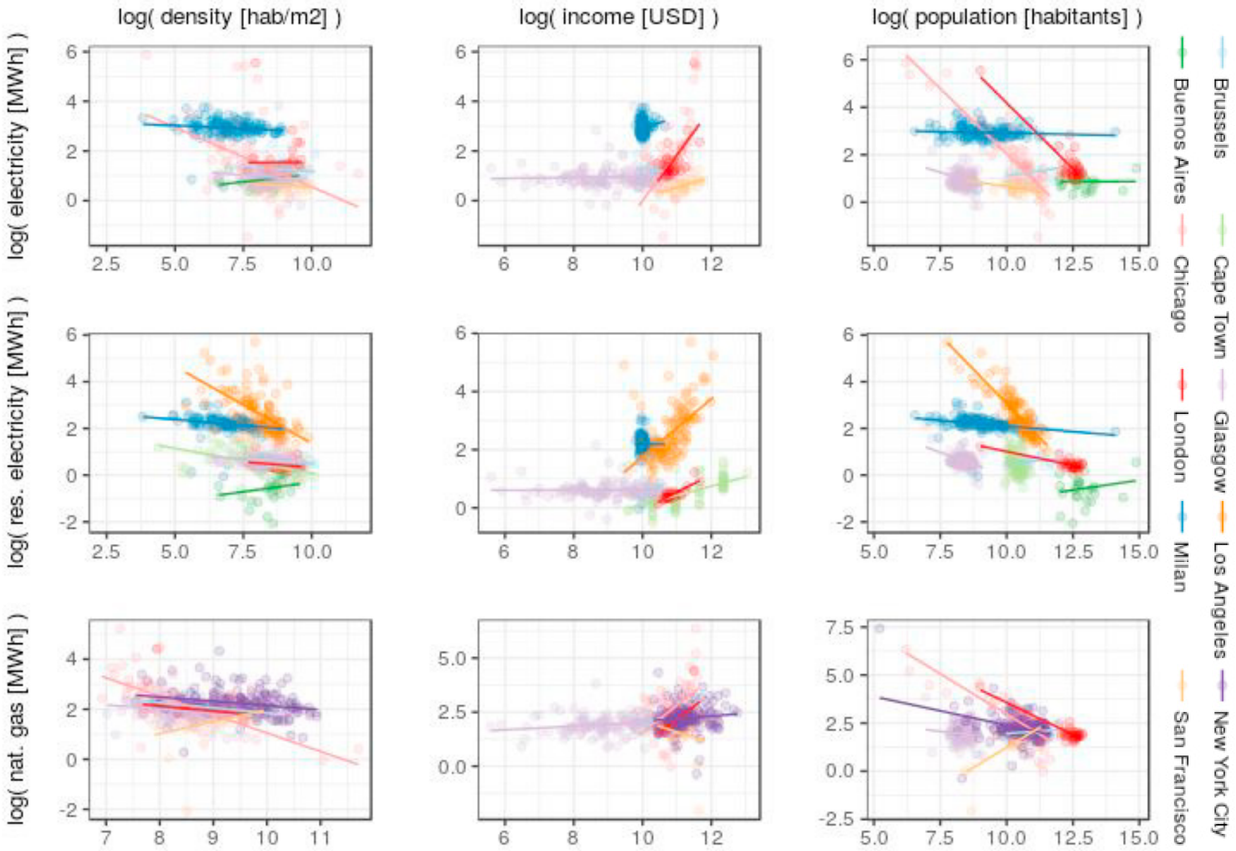

Fig. 1. Linear regressions showing the relation between selected energy-use indicators and urban features at micro-territorial unit level for each cities (when data is available). Energy-use indicators were normalized per capita.

Table 2. Scaling exponents and r squared coefficients for the linear regressions between energy-use indicators and urban features

	City	Alpha	r.squared	p.value	Alpha	r.squared	p.value	Alpha	r.squared	p.value
		Density			Income			Population		
Residential Electricity Use	Brussels	-0.0923	0.1341	0.1231	0.3618	1.76E-01	0.0739	0.0964	0.1247	0.1381
	Milan	-0.1002	0.0687	0.0022	0.0267	0.0001	9.23E-01	-0.0959	0.0741	0.0015
	Cape Town	-0.212	0.2412	0	0.3158	0.2884	0	-0.3837	0.0262	0.1463
	Buenos Aires	0.1618	0.034	0.3773	N/A	N/A	N/A	N/A	N/A	N/A
	London	-0.0961	0.0733	0.1275	0.6001	0.7096	0	-0.2368	0.6002	0
	Los Angeles	-0.6582	0.3582	0	0.9977	2.71E-01	0	-1.1681	0.7772	0.00E+00
	Glasgow	-0.0862	0.0434	0.0161	0.002	0.0001	0.9351	-0.4167	0.2197	0
Electricity use	Brussels	-0.0816	0.0195	0.5681	-0.2256	0.0127	0.6454	0.1663	0.0692	0.2766
	Milan	-0.0477	0.0137	0.1776	0.4481	0.0176	0.127	-0.0233	0.0039	0.4759
	Buenos Aires	0.1226	0.09	0.1451	N/A	N/A	N/A	N/A	N/A	N/A
	Chicago	-0.4795	0.1637	0.0016	1.9051	0.3246	0.00E+00	-1.094	0.7929	0.00E+00
	London	0.0074	0.00	0.9784	1.8967	0.3942	1.00E-04	-1.1086	0.7313	0.00E+00
	San Francisco	-0.0335	0.0065	0.7143	0.4305	0.4264	0.0007	-0.17	0.2267	0.0216
	Glasgow	-0.0853	0.0166	0.1399	0.0202	0.0021	0.5995	-0.3496	0.0601	0.0044
Natural gas use	Brussels	-0.2051	0.2951	0.0162	0.5316	0.169	0.0804	0.0987	0.0581	0.32
	Chicago	-0.7263	0.537	0	1.2537	0.2011	0.0004	-0.8411	0.6701	0
	London	-0.2062	0.0551	0.1885	1.2246	0.482	0	-0.669	0.7812	0
	San Francisco	0.4729	0.0938	0.1552	-0.5253	0.046	0.326	0.8345	0.3953	0.0013
	Glasgow	-0.134	0.0459	0.0133	0.0858	0.0426	0.0172	-0.1643	0.0149	0.1611
	New York City	-0.2768	0.1745	0	N/A	N/A	N/A	N/A	N/A	N/A

At this stage it can be argued that whilst this relative agreement with the trends which had been identified in studies looking at macroscale data points towards the existence of scaling effects, the observed heterogeneity also indicates that there are drivers specific to each city and which have a significant impact on and sometimes dominate over potential scaling effects. This finding highlights how studies which look at data at a more aggregate levels might overlook important variations in the drivers of energy consumption. It also emphasizes how local specificities strongly influence these relationships, and that mitigation and management strategies cannot rely on trends identified at the macroscale and in inter-urban comparisons, but need to look at more localized trends.

5. Discussion and Conclusion

The findings of this research state that whilst the trends which had been identified in studies looking at the macroscale can also be observed when looking at microscale data, the picture is far less clear, and that some cities are outliers to this trend. The relationships between these variables seems to be more complex when looking at microscale data. Such complexity is most likely due to the fact that at a smaller scale, numerous other influential variables become more dominant. This points the necessity to widen the variables taken into account especially in studies looking at microscale data, to capture these other influencing factors including climate, socioeconomic and political context.

Nonetheless, as each data intensive study (especially in urban energy use), the present research is also subject to important limitations, of which most concern the comparability of the data across the different cities. Datasets vary in base year, data type formats, units, especially regarding energy use, where the purpose of specific energy sources might vary greatly across different cities. Furthermore, the definition and size of the spatial MTUs varies greatly across cities, and while in some cases they are administrative units, in others they are independent municipalities.

Finally, the analysis of the energy use of 10 global cities at a microscale points towards areas where further research would be needed in order to better understand urban energy use drivers amongst developed and developing countries. In a global context where countries and cities aim to decarbonize their economies as well as shift their energy source to renewables, it is essential to better understand which are the drivers and the territorial organizations that are the most energy efficient. Only an evidenced-based approach that take into account the full complexity of cities could enable better decision making and develop mitigation and adaptation policy strategies for existing and new cities.

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