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Comment

Comment on Bettignies et al. The Scale-Dependent Behaviour of Cities: A Cross-Cities Multiscale Driver Analysis of Urban Energy Use. *Sustainability* 2019, *11*, 3246

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Abstract: Bettignies et al. examine power-law relationships between drivers of energy use and urban features at city and infra-city levels for ten different cities in six countries across four continents, featuring a wide distribution of urban indicators from various data sources. The authors employ univariate linear regression models using selected log-transformed indicators to investigate whether the intensity of energy use scales with urban indicators such as population size, density, and income. Bettignies et al. suggest that based on their findings, the urban energy-use drivers are in fact scale-dependent, and that their results reveal a substantial heterogeneity across and within cities. They reference this as why more consideration needs to be paid to local factors when devising urban policy. On this note, we argue that Bettignies et al. appear to have not only misunderstood the urban scaling literature they have cited, but have also employed flawed methodological design in their analysis that ultimately leaves their conclusions unsubstantiated.

Keywords: urban energy drivers; urban metabolism; urban scaling; scaling; energy; power law; multiscale analysis; cross-city analysis

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1. Introduction

Bettignies et al. [1], while attempting to investigate the application of urban scaling principles to urban energy consumption, argue for a greater consideration of local drivers and context in the development of policies that are to assist cities in their transition towards more sustainable consumption. On this note, while sympathetic towards the authors' overall call for a more proactive consideration of local factors, we would like to point out that we believe Bettignies et al.

A. Appear to have a number of misconceptions as to the nature of urban scaling frameworks, particularly in regard to the universality and 'scale-invariance' of characteristics when considering cities of different sizes and the application of urban scaling models to energy consumption;
B. Have employed flawed methodological design in their investigation of these urban dynamics;
C. In a number of cases, have analyzed and presented data with questionable scientific rigour that can lead to ambiguous or incorrectly interpreted results by readers.

2. A: Potential Misconceptions

Bettignies et al. contextualize their work within the urban scaling literature by stating that urban scaling studies have focused on "analysing how urban infrastructure, socio-economic or metabolic indicators change with either the population or the mean population density (e.g., [14,27–45])."—see the original paper by Bettignies et al. for these references.

Their bulk citation of the scaling literature suggests an apparent lack of in-depth engagement. The authors further rationalize their contribution by claiming that "even if a number of studies (e.g., [13,14]) rooted in a convincing theoretical framework [61] offer a macroscale understanding of cities' indicators with relation to their growth, it appears that cities should also be considered at a lower-scale level in order to account for their internal heterogeneity [46,62] but also to see how different cities are to one another at these more detailed scales". As such, the authors position their paper as one that seeks to shed light on the drivers of urban energy consumption "by considering the specificities and internal heterogeneity of cities which are not yet explicitly taken into account in the urban scaling field". To directly address their stated goal, they list three objectives:

1. To examine the existence of power-law relationships between urban energy intensity and population, population density, and median income of 10 cities belonging to different urban systems;
2. To examine the existence of such relationships across geographic units building up these urban areas, using what the authors dub Micro-Territorial Units (MTUs), to, as they put it, "investigate the scale (in-)dependency of urban energy power laws";
3. To determine whether such power-law relationships agree when fitting to MTUs of each urban area individually.

The authors' core thesis then appears to be that their objectives make it "possible to discover whether trends and drivers identified at city level by some of the above-mentioned studies are also true at smaller spatial scales, and thus showing whether energy use drivers are scale invariant". The problem is threefold.

2.1. Use of Scaling Frameworks to Study Heterogeneity

Firstly, it is a central thesis of 'complexity' and 'self-organized criticality' as applied to cities as organized complex systems that locally heterogeneous but interdependent interactions aggregate to result in macro-level behaviors [2,3]. References to Jacobs' seminal observations [3], which highlight this mixing of populations in cities as the driver of their success, remain prevalent across studies from both theoretical urban scaling and economic geography disciplines. Urban scaling frameworks, by nature, are designed to explore and address the universality and prevalence of these emergent macro-level average-aggregate urban phenomena with respect to urban size [4–7]. Hence, the attractiveness of such frameworks rests in their ability to infer wide-ranging, system-wide properties from a sparse set of system parameters. As such, an urban scaling perspective is inherently ill-suited for those interested in examining the effects of intra-urban heterogeneity at micro-levels, as the framework deals with mean responses of the system and not its local fluctuations. Local fluctuations are inherently assumed. Incorporating these frameworks as the sole source of one's methodology when the stated aim is to consider the "specificities and internal heterogeneity of cities" highlights a disconnect between the authors' stated aims and objectives.

2.2. Universality and 'Scale-Invariance'

Secondly, the authors appear to conflate small urban areas with arbitrary geographical units of small populations comprising urban areas (the authors' MTUs) when discussing the 'scale-invariance' of urban phenomena. The authors seemingly equate the universality of urban dynamics across size with the expectation that the same power laws that link urban size to prevalence of urban phenomena are to hold for the prevalence of such phenomena against size when considering MTUs that are decidedly not self-contained urban entities and are of arbitrary boundary definitions. The authors' investigation of scale-invariance by examining intra-urban geographic units therefore appears to rest on a misapprehension of the application of scaling frameworks. This is in fact explicitly discussed in the material cited by the authors, which formally outlines how using geographic boundaries that cut across functional urban areas would, from a statistical point of view, result in a vanishing of scaling effects [8].

2.3. Scaling of Energy Use with Population

Lastly, Bettignies et al. do not seem to have explored whether any of the urban scaling theoretical frameworks [5–7,9]—and not studies investigating the empirical existence of power laws in real world data [10]—have any reason to or do in fact claim to predict a power-law relationship between urban size and urban energy consumption. Such theoretical frameworks, including those cited by Bettignies et al. themselves, outline theoretical models that often rely on the core assumption that the urban metrics of interest are by-products of and commensurate with the number of human interactions that occur within cities. On this basis, these works put forward theoretical mechanisms that seek to explain the power-law relationships often empirically observed for economic output, urbanized area, and a few other metrics [11]. We note that we do not discount the ability of allometric frameworks to provide valid models of urban energy consumption. Arguably, one could, by extension to existing models, develop theoretical expectations for such scaling behavior for transport energy use. This would be due to the potentially strong coupling of mobility, and by extension transport, and urbanized area [5]. There is, however, no reason suggested by the scaling frameworks cited by the authors or the authors themselves, as to why aggregate energy consumption across various uses could potentially be an outcome of human interactions.

3. B: Flawed Methodology

Our contention regarding the authors' application of flawed methodology concerns their regression design, as the authors intend to examine the existence of power-law dynamics across cities and their MTUs, pooling together cities that are from different countries and continents. As Bettignies et al. point out, these scaling dynamics are often empirically investigated by calculating OLS estimates for the linearized log-transformation of power laws in the form

$$\log_{10} Y = \log_{10} Y_0 + \beta \log_{10} N \tag{1}$$

where Y is the urban phenomenon of interest, N population size, β the exponent determining the nature of the scaling regime, and Y_0 the general prevalence of the phenomenon [4,5,7]. Crucially, this formulation applies to cities which share a given general prevalence Y_0 and as such belong to a coherent urban system. Often, these urban systems sharing a common baseline prevalence of phenomena are intuitively taken to be the national groupings of cities [11,12]. The problem in the authors' work arises from their explicitly combining data from cities and MTUs from very different urban systems that have no reason to share an underlying baseline energy consumption, that is, Y_0 in Equation (1), as the authors themselves point out that the cities are from "...different economic development stages, as well as in different climatic zones...".

Consider, as an example, two urban systems in different climates: one extremely cold and the other temperate. Average total and per capita energy consumption across the cities of the former would have to be higher due to the additional heating demand caused by the climate for that urban system. This would result in the temperate urban system to be described by a smaller Y_0, comparatively. If cities from both urban systems are being used together to estimate a single β, which in essence quantifies the population-elasticity of a phenomena regardless of the choice of urban system, then data from each urban system need to be treated beforehand to eliminate the effect of a varying Y_0.

To apply the univariate regression meaningfully, the authors should have eliminated the intercept $\log_{10} Y_0$ by normalizing each unit's values against the average value of the urban system to which they belong before estimating the scaling regime β. We illustrate this in Figure 1. In panel A, we show randomly generated values for N and Y and their individual regression fit for four urban systems with different values of the intercept $\log_{10} Y_0$. See online Supplementary Materials for code and data used for in Figure 3. This is similar to the authors' application of their univariate model to MTUs of each city individually. As an attempt to duplicate the regression plots presented by the authors in Figure 3 of the original paper, panel B demonstrates the result of not normalizing values before calculating the regression fit when pooling the urban systems together. Finally, in panel C, we normalize values for each city by the mean value across the urban system to which it belongs before estimating the regression coefficients. Once again, this is a peculiar oversight given that the work by Bettencourt and Lobo [12] cited by the authors is dedicated to setting out such an approach using cities belonging to various European urban systems.

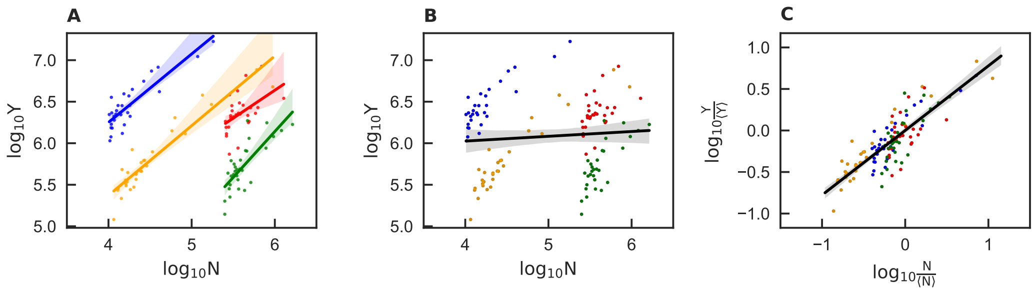

Figure 1. Scaling of phenomenon Y with population N for four synthetic urban systems (**A**), the OLS fit to all the cities combined (**B**), and the OLS fit to mean-normalized values (**C**).

4. C: Analytical Rigour

In the previous two sections, we outlined issues arising from what we believe has been the authors' lack of engagement with the particularities of the scaling literature. In this section, we point out a number of cases where the paper could have been more rigorous with regard to the way data are analyzed and/or presented.

4.1. Correlation of the Independent Variables

In addition to population count, Bettignies et al. consider the scaling of their energy indicators against two other independent variables. It would have been useful if the authors had provided an examination of a possible correlation between population and their two additional variables, i.e., population density and median income, as the two would be expected to be correlated with population themselves in scaling frameworks [5,11,12].

4.2. Performance Measures of Regression Models

The authors provide values for the coefficient of determination and *p*-values as diagnostic statistics. While appreciated, it perhaps would have been more helpful to also provide 95% confidence intervals for the slopes estimated. Without considering the confidence intervals, it would be difficult to interpret the scaling regime with any certainty, as it is unclear whether, for example, a super-linear exponent—a positive slope in the authors' work as they regress per capita values against population—remains as such over the confidence interval.

4.3. Descriptive Statistics of the Input Data

Bettignies et al. provide descriptive statistics of their input data from each city mainly through providing a number of kernel density estimations of the data from the MTUs. It is unclear as to why the authors felt the need to only present the kernel density estimates, rather than also for instance, a histogram of the actual data. Considering that a significant proportion of their description of their data is communicated through these kernel density figures, some small amount of information about the implementation vis a vis the kernel bandwidth would have been helpful. While the authors present the kernel densities as those of "...the studied variables for each city, at microscale in a logarithmic scale", these are clearly estimated from the log of the values with the x-axis relabeled to appear logarithmic, rather than plotting original values on a logarithmic axis. Bettignies et al. appear to be unaware of this error throughout the manuscript. The authors appear to only refer back to these incorrect kernel estimates rather than the actual distribution when reporting on the standard deviation, skewness, mean, and mode of the data. Their statements such as "Regarding uniformity of the population distribution, Glasgow, Cape Town and London have very little skewness and small spread around their mode…" are consequently unsubstantiated. Similar statements could arguably be considered trivial given the authors' use of log values, choice of kernel function and kernel bandwidth. Figure 2 demonstrates the potential significance of this error by considering the population density values for the 33 boroughs of London. In panel A, we show the normalized histogram of the data along with its kernel estimation plotted on a logarithmic axis. In contrast, panel B shows normalized histogram and similar kernel estimation for the log values. The substantial and significant difference between the two kernel density estimates is clearly evident.

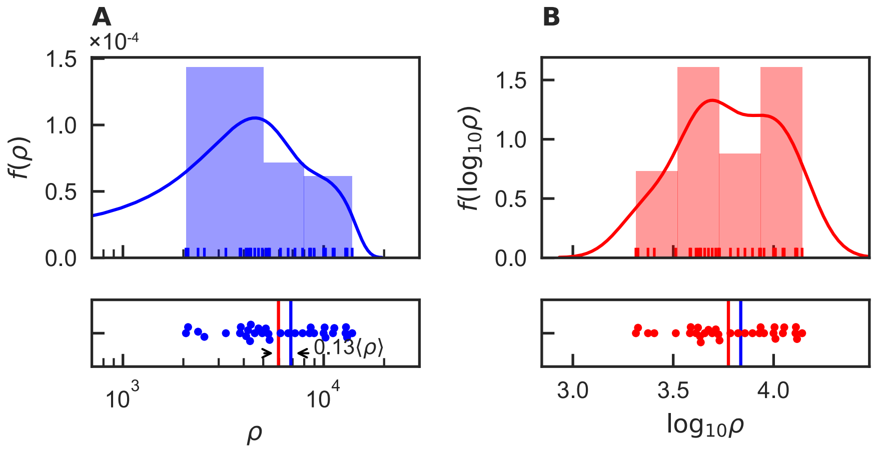

Figure 2. Normalized histogram, kernel density estimates, and swarmplot of (**A**) actual values for population density and (**B**) the log of population density for 33 London boroughs. Note that the blue vertical lines in the swarm plots show the mean of the true population density while the red vertical lines show the mean of the log values with the difference between the two means, $\langle\rho\rangle - 10^{\langle\log_{10}\rho\rangle}$, 13% of the value of the correct mean, $\langle\rho\rangle$.

5. Final Remarks

As outlined above, aside from employing flawed methodological design and incorrectly analysing data, Bettignies et al. appear to have a number of misconceptions as to the nature of the urban scaling frameworks. We reiterate that we are sympathetic to the authors' view that a better understanding of intra-city heterogeneity is required for policy purposes when considering urban energy use. Particularly, we do not disagree with the statement that "…urban energy use is complex and driven by a multitude of intra-urban drivers which could benefit from studies exploring their heterogeneous intra-urban patterns". However, we strongly believe that the manner by which the authors arrive at this argument is based on an unnecessary misrepresentation and misapplication of the urban scaling frameworks that ultimately leaves their conclusions unsubstantiated.

Supplementary Materials: The Jupyter notebook and London data used in the creation of the figures are available online at https://github.com/cip15ha/sustanability-comment (accessed on 28 March 2022).

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