Electricity Consumption Described by Urban Scaling Laws

The case of Portugal using two definitions of urban area

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Introduction

There is no doubt that cities are hubs for, not only production, but also consumption. The concentration of wealth and consumption in cities is even larger than the concentration of population which, since 2009, is larger than 50% [1-3]. With the foreseen growth of urbanization it is imperative to study the dynamics that drive the functioning of cities and the respective consumption of resources such as Energy.
Inspired by the connection between physiological characteristics of some biological organisms and their body mass, Bettencourt et al. tested the existence of a scale relation between city size (measured in terms of its population) and a set of indicators. This relation is described by the formula:

$$I = \alpha S^{\beta}$$

I - indicator; α - normalization constant; S - city size; β - scaling factor

The scaling factor β represents the elasticity of the indicator in relation to the city's population. This elasticity gives the variation of the indicator caused by the variation of population.
In relation to the total electricity consumption of a city, the scaling law obtained was a "super-linear" one, e.g., the value of β was larger than 1.

Urban boundaries

One of the main problems that emerge when studying urbanization or any subject related with cities' populations is the definition of what is a city. Usually, the approach taken is to use the administrative definitions as it is something that already exists for which data is already gathered [5].

Administrative boundaries

Portugal is divided in different layers of administrative areas. The municipality (concelho) is the lowest level that is still reasonably stable. They were defined throughout history mainly due to the distribution of *Forais*, documents that assigned

the rights and administration of a certain area of land. Municipalities are divided into "freguesias" (similar to parishes) which can be created if such is proposed by the corresponding municipality. Freguesias can be labeled as Urban, Semi-urban or Rural according to criteria of density and total population[7], [8][1].
The creation of urban municipalities definition intended an approximation to the urbanization rate in 1994 (50%) and to the total number of official cities (123). Two criteria were used to define urban municipalities and are presented in Table 1 which led to a total of 123 urban municipalities in mainland Portugal.

	Urban	Semi-urban	# Municipalities
Condition 1	15%	50%	24
Condition 2	40%	-	99

Table1: Criteria of urban municipalities (percentage of population)

For this labeling we used data from 2001 as only in this year is the data discriminated at the level of freguesia. For the following years there are only estimates which are done until the level of municipalities. We considered the labels constant throughout all the years of the analysis.

Cities and their definition

There is an official statute of city in Portugal to which places may candidate themselves to. To become cities they have a population above 8,000 inhabitants and a number infrasctuctures. For the scope of this work, we consider the data of the work done by INE (portuguese National Institute of Statistics) which comprises a total of 123 cities in mainland Portugal.

Application of urban scaling laws

To perform the study on urban scaling laws in Portugal we used electricity consumption that is described by the following equation:

$$El_{mun,t} = \alpha S_{mun,t}^{\beta}$$

$El_{mun,t}$ - Consumption of electricity in the municipality at year t [kWh]; α - constant [kWh.habitants$^{-\beta}$]; $S_{mun,t}$ - city size of the municipality at year t [habitants]; β - scaling factor of electricity demand (dimensionless)

Data and methodology

Regarding the demographic data for the municipalities we gathered the values of total population for the years between 1994 and 2008. For cities we used the total population and population density for the year 2001 (the only year that could be crossed with energy data). All the demographic data was taken from the INE online database.

[1] This classification was valid until the end of 2009, although it is still used in some studies.

The source of the data about the yearly electricity consumption between 1994 and 2008 is DGGE (Direcção-Geral de Geologia e Energia), the portuguese energy agency.
For the regressions made we used Stata 11, which is a software package for statistical analysis.

Municipalities

For the urban municipalities we did an yearly analysis throughout 15 years (from 1994 until 2008) to obtain, not only the fit of the Portuguese reality to an urban scaling law as described by Bettencourt et al., but also how it evolves in time.
To simplify the use of the equation we applied the logarithm so the expression used was:

$$\ln(El_{mun,t}) = \ln(\alpha) + \beta\ln(S_{mun,t})$$

Year	ln(α)	α	β	R^2
1994	6.64	765	1.11	0.77
1995	6.63	758	1.12	0.77
1996	6.70	811	1.12	0.78
1997	6.77	868	1.12	0.78
1998	6.88	975	1.11	0.78
1999	7.08	1,186	1.10	0.79
2000	7.13	1,250	1.10	0.79
2001	7.25	1,409	1.09	0.79
2002	7.42	1,675	1.08	0.79
2003	7.46	1,743	1.08	0.80
2004	7.59	1,984	1.07	0.80
2005	7.74	2,308	1.06	0.80
2006	7.77	2,378	1.06	0.80
2007	7.98	2,922	1.04	0.79
2008	8.11	3,315	1.03	0.79

Table 2: Urban scaling coefficients for Portuguese municipalities

Of the results presented in Table 2, the most intriguing is the decreasing trend of the coefficient as electricity consumption was following more closely the distribution of population, e.g., evolving towards a linear scaling law.
Other observation that can be made about Table 2 is the increase in the values of ln(α). This may be explained by two facts: the growth of electricity consumption per

capita along the years and a compensation for the decrease of the β_{el} coefficient as already discussed.

Cities

As it was not possible to collect data of electricity consumption for cities we used the consumption of municipalities in a way that accounted for both the urban and rural values. For that we assumed that rural electricity consumption grows linearly with population. That way we can define electricity consumption as:

$$El_{mun} = \alpha_{rur} S_{rur} + \alpha_{urb} \sum_{i=1}^{n} S_i^{\beta_{el}}$$

α_{rur} - constant applied to rural areas; α_{urb} – constant applied to urban areas; S_i –Size of each city belonging to the municipality

However, as there are only a few municipalities with more than one city, we disregarded these cases. Therefore, the equation can be simplified to:

$$El_{mun} = \alpha_{rur} S_{rur} + \alpha_{urb} S_{urb}^{\beta_{el}}$$

For the analysis we used a nonlinear least squares method already included in Stata11.

α_{rur}	α_{urb}	Coefficient β_{el}	R^2
4,664	1,171	1.11	0.88

Table 3: Urban scaling coefficients for Portuguese cities in 2001

Although the evaluation of consistency between these results and the ones presented on the previous section would require additional points we can make a direct comparison of the 2001 coefficient values obtained. The β coefficient seems close to the one obtained for urban municipalities in the year 2001 (1.09) but the value of the constant α_{urb} (which compares with the value of α for 2001 - 1,409) is lower, maybe to compensate the slightly higher value of β_{el}. This discrepancy also might indicate that the average value per capita is lower for cities than urban municipalities.

Final remarks and ongoing work

In Portugal, the definition of cities and urban areas is very attached to the concept of municipality, although in many cases the reality overcomes their frontiers as it is the case of the two largest cities (Porto and Lisboa). However, the availability of data and the official definitions led us to use as urban areas some of the municipalities and cities as defined by INE. Urban scaling laws were applied to both urban criteria using electricity consumption.

For the first criterion, it was possible to conduct a regression analysis in a time frame of 15 years where we found the most surprising trend of the study. Along the

years the scaling coefficient decrease to values close to one which means that the relation between electricity consumed and the city size was becoming linear. To explain this linearization one should separate the different uses of electricity into sectors.
Currently we are developing an analysis dividing the consumption in residential use and the rest of the economy applying more explanatory variables to the latter.

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