Integrating energy and land-use planning: socio-metabolic profiles along the rural-urban continuum in Catalonia (Spain)

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Abstract

Abandoning fossil fuels and increasingly relying on low-density, land-intensive renewable energy will increase demand for land, affecting current global and regional rural–urban relationships. Over the past two decades, rural–urban relationships all over the world have witnessed unprecedented changes that have rendered their boundaries blurred and have lead to the emergence of "new ruralities." In this paper, we analyze the current profiles of electricity generation and consumption in relation to sociodemographic variables related to the use of time and land across the territory of Catalonia, Spain. Through a clustering procedure based on multivariate statistical analysis, we found that electricity consumption is related to functional specialization in the roles undertaken by different types of municipalities in the urban system. Municipality types have distinctive metabolic profiles in different sectors depending on their industrial, services or residential role. Villages' metabolism is influenced by urban sprawl and industrial specialization, reflecting current "new ruralities." Segregation between work activity and residence increases both overall electricity consumption and its rate (per hour) and density (per hectare) of dissipation. A sustainable spatial organization of societal activities without the use of fossil fuels or nuclear energy would require huge structural and sociodemographic changes to reduce energy demand and adapt it to regionally available renewable energy.

Keywords

Energy metabolism; Electricity; MuSIASEM; Distributed energy generation; Functional urban specialization; Renewable energy; Socio-metabolic profiles.

1. Introduction

The end of cheap fossil energy and the growing consequences of climate change are setting the scene for current and future political disputes about society's transition toward renewable energies (Abramsky 2010).

Abandoning fossil fuels and increasingly relying on dispersed and low power density renewable energy will increase demand for land to generate energy (Scheidel and Sorman 2012; Smil 2008). The spatial dimensions of energy provision, previously externalized and dismissed by the high-consuming global north, will regain importance affecting global and regional rural–urban relationships.

Thanks to abundant fossil fuels, neoliberal globalization has brought about multidimensional unprecedented changes in rural–urban relationships (Brereton et al. 2011; Smith 2007). Growing networked interconnections and increased spatial mobility (Marsden 2009) have rendered the traditional boundaries between rural and urban areas more blurry (Tacoli 2003). Diffuse urbanization, particularly in western industrialized societies, has lead to the emergence of "new ruralities," in terms of rural areas that increasingly share urban features. The sustainability of such a rural–urban relationships based on fossil fuels is, thus, directly related to the transition to renewable energies.

Most of modern renewable technologies generate electricity, which is claimed to be versatile and ideal for managing uncertain future mobility (Gilbert and Perl 2010). Growing debate has focused on desirable, feasible and efficient models of transforming electrical grids. Combining advances in information and communication technology (ICT) and in electrical grids design, "smart grids" are proposed to enable bidirectional communication along with power flow between the consumer and the grid (Farhangi 2010; Rifkin 2011; Usman and Shami 2013). Distributed energy generation has also been presented as a new paradigm to relocate generation and consumption of energy closer one another (Ackermann et al. 2001; Alanne and Saari 2006; Pepermans et al. 2005). By reducing overall consumption and environmental impacts, distributed generation emphasizes decentralization and small- and medium-size renewable power plants facilities.

The above literature on redesign of electrical grids is mainly concentrated on the technical feasibility of implementing such technological systems. Although mentioning environmental benefits for sustainable development, few references are made to the spatial and sociodemographic reconfiguration they may imply or require. The promotion of such a new paradigm means taking low-density and land-intensive renewable energy, as the basis of the energy system. This requires careful consideration of both the spatial and social distribution of present and future scenarios of energy consumption and their compatibility with available renewable energy resources. In this paper, we aim to contribute to that work by studying the present situation in Catalonia, Spain.

We analyze the current profiles of electricity generation and consumption in relation to sociodemographic variables representing the use of time and land across the territory of

Catalonia for the year 2001, the most suitable date for obtaining all required data[1]. Thus, we study profiles of "societal metabolism", understood as the set of conversions of energy (and material) flows occurring within a society which are necessary for its continued existence (Giampietro et al. 2009).

By identifying differences in land and time use and their associated energy flows within the Catalonian region, we derive a typology of municipalities through a clustering procedure based on multivariate statistical analysis. This enables us to identify processes explaining the relationship between spatial distribution of energy metabolic profiles and sociodemographic structures and land uses. Comparison across this typology highlights the relevance of urban sprawl and the related emergence of "new ruralities" typical of late-industrial societies where villages are connected to urban centers through commuting. Functional urban specialization in industrial, services or residential activities increases the rate (per hour) and density (per hectare) of electricity consumption both in market and household sectors and depends upon a centralized generation system.

After presenting details about the Catalonian case study and our methodological approach in Sects. 2 and 3, we present in Sect. 4 the typology of municipalities and the metabolic profiles it helped to identify. In Sect. 5, we discuss the main findings, identifying plausible qualitative changes in urban densities and in urban hierarchy[2] that could help with adjusting current energy consumption profiles to increase their compatibility with a distributed energy system. We close, in Sect. 6, with a set of reflections on the strengths and weaknesses of the approach employed here and provide some recommendations for future work.

2. Background: urbanization and the spatial dimension of Catalonia's energy metabolism

Catalonia (see Fig. 1) is one of the most densely populated, urbanized and industrialized regions of Spain. With a population of 7.5 million, it represents 16 % of the Spanish population (INE 2012) and it accounted for 18.7 % of total GDP (INE 2007) as well as for 19 % of primary energy consumption in Spain in 2009 (ICAEN 2009; IEA 2012). Regarding electricity, Catalonia accounts for 20 % of total consumption in Spain, thus being the largest electricity consumer in Spain (REE 2010).

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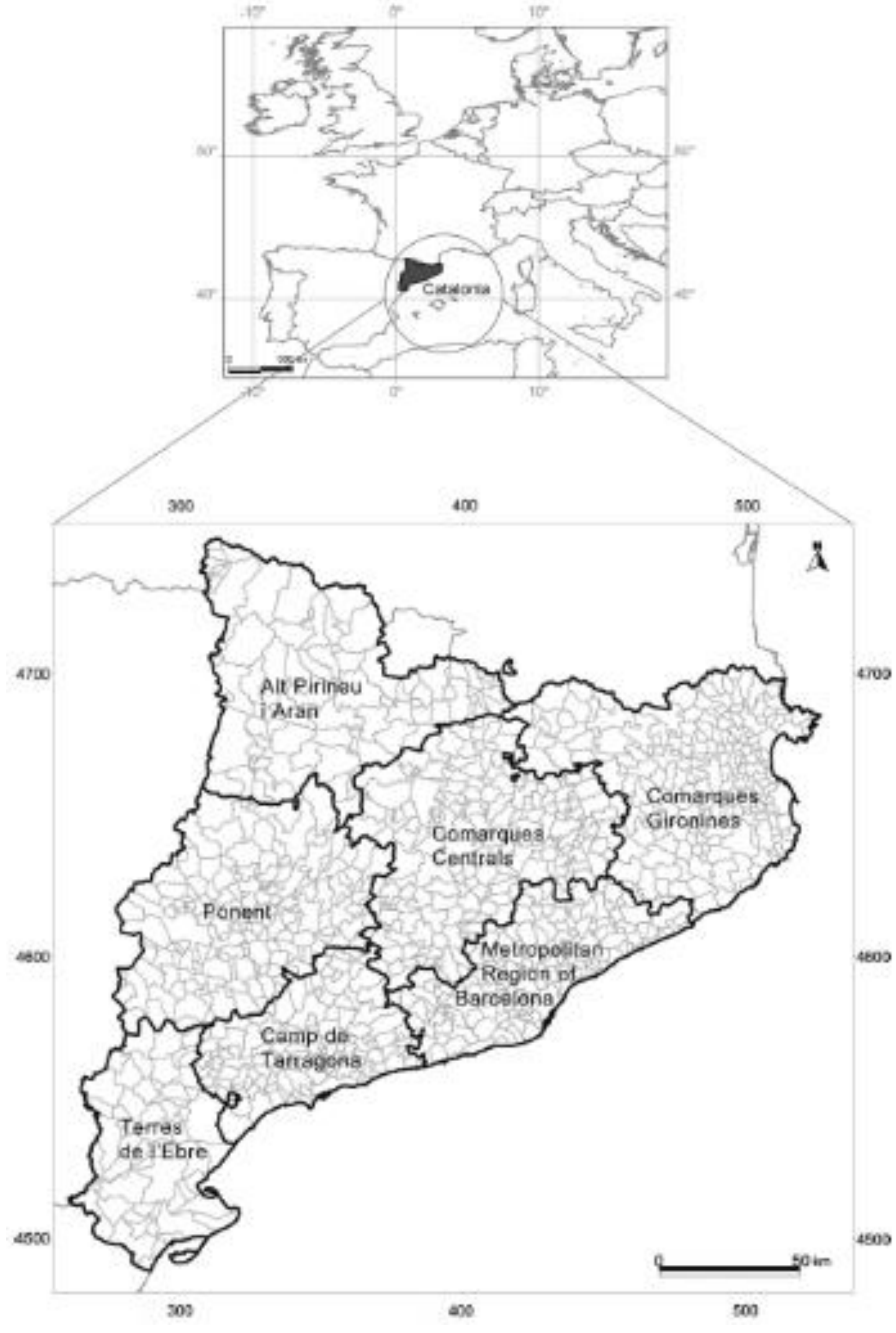
[1] See Sect. 3, about methods for details.

[2] Throughout the paper, we refer to urban hierarchy as the structure of the network of cities in terms of the relative socioeconomic and demographic importance of the group of cities that form the urban system and their relationships. Thus, the urban hierarchy of an urban system based on polycentric compact medium sized cities and villages with mixed uses is qualitatively different than that of a central big city, surrounded by a dispersed conurbation of a low-density mono-functional urban sprawl.

Fig. 1. **a** Location map of Catalonia within Europe; **b** administrative division of planning spatial entities “àmbits territorials” [regions of the general territorial planning of Catalona (Gencat 1995)]. *Sources*: ICC (2012) and Gencat (1995).



Several studies have shown the influence of different socioeconomic sectors in driving the high energy demand of Spain and Catalonia, highlighting the importance of the transport and residential sectors (Alcántara and Duarte 2004; Alcántara and Padilla 2003; Ramos-Martín (Coord.) 2009; Ramos-Martín et al. 2009; Roca and Alcántara 2001). Growing energy consumption in the market economic sectors has been used for employing a larger active population in low labor productivity activities such as construction and services[3] (Ramos-Martin et al. 2009). The household sector, meanwhile, has increased its energy consumption due to: (1) Catalonia's convergence with European material standard of living and (2) the increase on the total number of households (31 % growth between 1981 and 2001) which reflects not only population growth but also structural change from nuclear families toward more single-parent and single-person households (Gamboa 2009; Ramos-Martín et al. 2009). Catalonia's energy metabolism, thus, faces a great difficulty of increasing labor productivity to sustain an aging population without increasing energy consumption[4] (D'Alisa and Cattaneo 2012; Ramos-Martín et al. 2009).

This growing energy consumption in both market and household sectors is related to the increased value of real estate and the urbanization boom, in particular urban sprawl. The urban sprawl of Catalonia with its main focus in the Barcelona Metropolitan Region (BMR) but also reproduced in other smaller metropolitan centers (Reus-Tarragona, Girona-Figueres and Lleida-Segrià) has established a network of urban systems (FMR 2009; GENCAT 1995; Nel lo 2001). The growth of urban areas has meant not only the growing occupation of land, but also new urban–rural relationships and the diffusion of new lifestyles in rural areas, which have been converging with urban ones. Urban centers influence more and more the development of the surrounding rural areas through new patterns of mobility, teleworking, second homes and new ecotourist activities associated to natural protected areas (FMR 2009). These changes have been energetically fueled mainly by fossil energy, consumed through the rise of private automobile mobility and the industrialization of agriculture. However, they are also dependent on a centralized electricity generation system characterized by a great distance between generation and consumption (see Fig. 2). Power plant siting is heavily skewed toward the south (nuclear, combined cycle, large hydro and recently wind farms) and toward the mountains in the north with hydropower production. Energy consumption, by contrast, has always been highest in the central urban, industrial and northern touristic regions (Saladié 2011). Moreover, the system is concentrated in few power plants that are responsible for most of the generation. 70 % of the generation in 2009 originated from just three nuclear power plants, seven combined cycle units and five thermal stations. About forty large hydropower stations (bigger than 10 MW of installed capacity) accounted for an additional 8 %. The remaining 22 % of electricity is generated through power plants of \50 MW of installed capacity, mainly of renewable energy, waste-to-energy plants, small hydro stations (\10 MW) and combined heat and power (CHP)[5] (ICAEN 2009).

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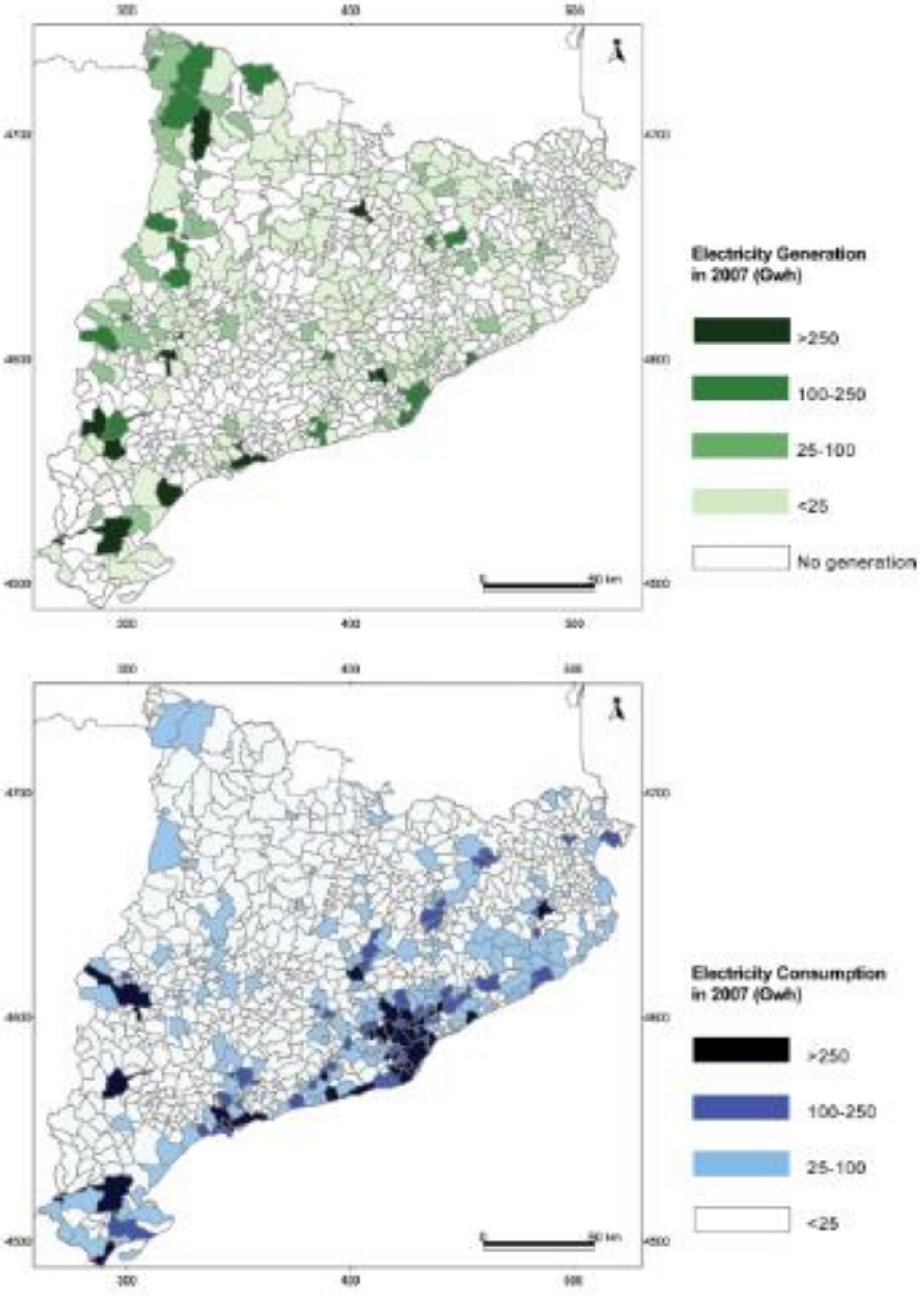
[3] High correlation between energy consumption and GDP, in Catalonia and Spain, as in many other western industrialized countries explains why growing GDP, despite low productivity of labor, has led to growing energy consumption, see Ramos-Martín et al. 2009.

[4] An aging population and the increasing isolation of citizens in single-person households puts a growing burden either on unpaid work for maintenance and care, or through its substitution by services bought in the market which would increase the overall energy consumption (D'Alisa and Cattaneo 2012).

[5] Although Spain is net exporter of electricity, providing 8.333 Gwh to France in 2010, within Spain, Catalonia is a net importer of electricity, demanding from other regions of Spain 5.545 Gwh in 2010 (REE 2010).

Fig. 2. Geographic distribution of electricity generation **(a)** and consumption **(b)** in Catalonia in 2007, at municipality level (LAU2). *Source*: Own elaboration from ICC (2012) and ICAEN (2010).



The interaction between the energy metabolism and the creation of landscapes has been studied in the Barcelona Metropolitan Region. Research has developed tools for quantifying the relationship between urbanization, the historical loss of energy efficiency of agriculture and the functional disconnection between land uses previously integrated in the agroforestry mosaic[6] (Cussó et al. 2006; Marull et al. 2007; 2010). This has usefully assessed the environmental impact of urbanization on the immediate surrounding environment[7] and has mainly explored the metabolism of the agricultural sector. By mapping hours of available human time and energy throughput, using GIS techniques, Lobo and Baena (2009) identified a spatial segregation between work and residential activity in the Metropolitan Area of Barcelona. They found three clusters of activity, two of mutual exclusion and a third large area of work and residence co-occurrence. Total energy throughput tended to concentrate in areas of fast growth coinciding with exclusivity of either industrial work or residential activities. Here, we follow Lobo and Baena's (2009) initiative in combining spatial and socioeconomic data, in order to complement these previous studies by relating sociodemographic structural characteristics to energy metabolic profiles across the rural–urban continuum of Catalonia.

3. Methods: applying MuSIASEM to relate metabolic profiles to a typology of municipalities

In order to explore relationships between energy metabolism and the spatial distribution of sociodemographic and land-use characteristics, we apply a two-steps methodological design. First, we calculate a combination of conventional indicators capturing multiple characteristics usually associated to "rural" and "urban" areas and indicators derived from the Multi-Scale Integrated Analysis of Societal and Ecological Metabolism (MuSIASEM) approach (Giampietro et al. 2009). Second, using multivariate statistical techniques applied to the set of indicators, we derive a typology of municipalities with distinct metabolic profiles.

3.1. Indicators of rural-urban characteristics

In the Spanish and Catalan context, as in other European regions, certain characteristics in municipalities have been identified as relevant indicators of contemporary "ruralities." Low population density, progressive aging of the population and a high degree of farming-related occupation are among the foremost characteristics, followed by second-homes ratio or self-employment (Entrena-Durán 1998; Ocaña-Riola and Sánchez-Cantalejo 2005; Prieto-Lara and Ocaña-Riola 2010). Table 1 shows the indicators we specifically used to characterize municipalities regarding their urban–rural characteristics. Some variables such as agrarian people's occupation and land use are already captured by MuSIASEM indicators.

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[6] The historical loss of energy efficiency of agriculture is expressed by the progressive reduction of the energy return on investment (EROI) from mid-nineteenth century to present, brought about by the introduction of fossil fuel inputs and the functional disconnection of forest, pasture and agricultural lands previously managed integrally (Cussó et al 2006, Marull et al 2007).

[7] The growth of built-up areas and infrastructure sites occupying more and more space in the land matrix with the rest of the landscape remaining residual in the Barcelona Metropolitan Region (BMR) has reduced the ''landscape efficiency'', the ability of the landscape to satisfy human needs while maintaining the healthiest ecological patterns and processes, such as ecological connectivity (Marull et al 2010).

Table 1. Rural-urban indicators with their description, unit of calculation and dimension they formally represent.

Variable name	**Variable description and unit of calculation**	
	Socio-demographic characteristics	**Indicators of...**
Dependency ratio	Ratio between active population (15-65 years old) and the dependent part (0-15 and over 65). Expressed in percentage (%).	Aging and population structure
%Residing Workers	Fraction of paid work human activity coming from population living in the same municipality. Expressed in percentage (%).	Economic dynamism
%Commuting Workers	Fraction of paid work human activity taking place in the municipality coming from population living in other place. Expressed in percentage (%).	Role played in the urban system Daily labour mobility needs
%Active Residents working outside	Fraction of the active population living in the place which works outside. Expressed in percentage (%).	
	Land use and settlement pattern	
Distance to >5000 inhab. population centers	Distance to other population centers of more than 5000 inhabitants. Expressed in kilometers (Km)	Access to services Daily labour mobility needs
%Nucleated urban area	Proportion of the urbanized area being core centers of population. Expressed in percentage (%)	Structure of the settlement pattern
%Low density dispersed urban area	Proportion of the urbanized area being low density dispersed urbanizations. Expressed in percentage (%)	
%Industrial park area	Proportion of the urbanized area being industrial parks. Expressed in percentage (%)	
%of apartment buildings	Proportion of housing buildings being apartment complexes. Expressed in percentage (%)	
%of second homes in housing	Proportion of housing buildings being second homes. Expressed in percentage (%)	
Population density urban area	Density of population in the urbanized area. Expressed in inhabitants per square kilometer (inhab/km^2)	
Population density municipality	Density of population in Total Available Land of the municipality. Expressed in inhabitants per square kilometer (inhab /km^2)	

3.2. The MuSIASEM approach at municipality level

In the MuSIASEM approach, information is combined from three different domains—demographic, economic and biophysical (i.e., exosomatic energy consumption)—at different hierarchical levels in order to generate intensive variables for characterizing the societal metabolism of a particular system.

Based on Georgescu-Roegen's flow–fund model (Georgescu-Roegen 1971), different types of variables are distinguished, depending on the role undertaken in the production process. "Flow" elements enter but do not exit the production process or, conversely, exit without having entered the process. The main flows analyzed here are electricity generation and consumption [total electricity consumption (TEC) and total electricity generated (TEG) see Table 2]."Fund" elements are agents that enter and exit the process, transforming input flows into output flows. In our case, the main funds are human activity and land use [total human activity (THA) and total available land (TAL) see Table 2]. Using ratios between flows and funds, we can derive intensive variables, useful to generate benchmarks for comparison, such as the exosomatic metabolic rate (EMR) (MJ/hour of activity) or the TEC per hectare (MJ/ha) (see Table 2). In our case, because electricity is mainly consumed in urban areas, and the agricultural sector does not play a major role in electricity consumption[8], we always calculate TEC per hectare with reference to urbanized area (the sum of all paved land in the municipality being residential complexes, population centers or industrial parks).

Figure 3 shows the different fund elements we have considered at different hierarchical levels: the whole system (municipality) with the THA (Level n) and the total available land (TAL) (Level n + 1), the colonized (COL) and non-colonized land[9] (NCL) (Level n), the market [paid work (PW)] and household sectors (HH) (unpaid work and all the rest of nonworking human activities) (Level n - 1) and the sectoral distribution of land- and time use 9 across agriculture (AG), services (SG) and productive sectors (PS) (industry or building and manufacturing activities) and household types (Level n - 2). Table 2 provides a detailed overview of the associated indicators in terms of description, calculation and purpose within our analysis.

MuSIASEM can be applied at different geographical scales, either a nation-state (Eisenmenger et al. 2007; Falconí-Benítez 2001; Gasparatos et al. 2009; Iorgulescu and Polimeni 2009; Ramos-Martín 2001; Ramos-Martin et al. 2007; Sorman and Giampietro 2011), a region (Ramos-Martin et al. 2009) or a municipality. Aiming to get the highest possible resolution of spatial distribution of energy metabolic profiles, we have conducted our analysis at the municipality level. This was the lower geographical scale where the most disaggregated data of all dimensions considered were available. The analysis at multiple scales and dimensions, employing intensive variables, makes MuSIASEM useful for exploring how similar absolute levels and per hectare densities of municipal electricity consumption are related to the prevalence of different sectors and rates of electricity consumption per hour of activity. The intensive flow/fund variables obtained by relating flows (in this case electricity) to funds (in this case land and time use) are also of help for comparing municipalities with different population sizes and land uses.

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[8] As later shown in Table 6, on average, the maximum electricity consumption in agriculture is around 10 % in small villages.

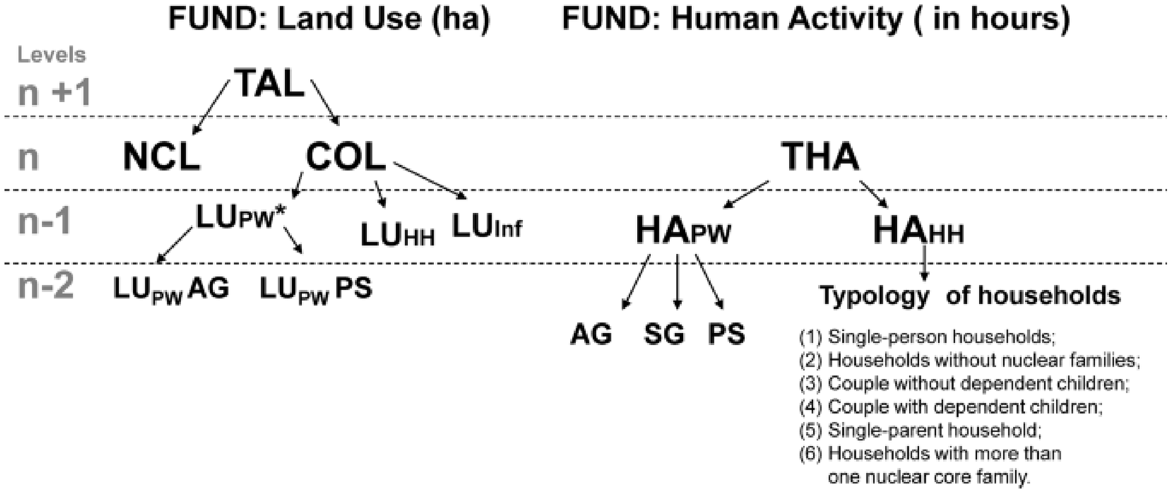
[9] We consider forests and water bodies as "non-colonized land" with the aim to follow the initially developed categories of MuSIASEM. However, in our case, a Mediterranean area in South Europe, forests and water bodies are strongly influenced by human activities. Here, "non-colonized" is used with the meaning of non-agricultural, non-urbanized land.

Table 2. MuSIASEM indicators with their description, calculation and usefulness for the purpose of the analysis.

Level	Acronym	Variable name and explanation	Unit and calculation	Usefulness for our purpose/ Fund or flow?	Statistical sources
		Socio-demographic characteristics			
n	THA	**Total Human Activity,** Total human time a society has available for conducting different activities.	Hours (h) (total population times 8760h of a year)	**Fund**	**IDESCAT 2001**
n-2	$HA_{PW\ i}$	**Human Activity dedicated to work, paid through the market, in the given sector ("i") and municipality**. We divide the working population in agriculture (AG), productive sector (PS) and Services and Government (S&G).	Hours (h) or share (%) (total population employed in the sector times the average daily working hours a year)	The sectoral distribution of activity indicates degrees of "rurality-urbanity"	IDESCAT 2001
n-2	% HHTypei	**Fraction of the population living in a given household type "i".** We divide the household types in the six categories given by Census data (IDESCAT 2001): (1) unipersonals; (2) households without nuclear core families; (3) Couple without dependent children; (4) Couple with dependent children; (5) Single-parent household; (6) Households with more than one nuclear core family.	Expressed in percentage (%)		IDESCAT 2001
		Land use			
n	TAL	**Total available land**: Total available surface of the municipality	Expressed in hectares (ha)	**Fund**	**GENCAT 2002**
n-1	NCL	**Non-colonized land:** surface covered by forests and water bodies.	Expressed in hectares (ha) or in percentage (%)	The land use pattern indicates degrees of "rurality-urbanity"	GENCAT 2002
n-3	$LU_{PW}AG$	**Agricultural land:** surface dedicated to agricultural activities	Expressed in hectares (ha) or in percentage (%)		GENCAT 2002
n-3	$LU_{PW}PS$*	**Surface dedicated to productive sector (out of Total Available Land)**	Expressed in hectares (ha) or in percentage (%)		GENCAT 2002
n-2	LUinf	**Surface dedicated to infrastructures**	Expressed in hectares (ha) or in percentage (%)		GENCAT 2002

n-2	LU_{HH}	**Surface dedicated to residential areas.**	Expressed in hectares (ha) or in percentage (%)		GENCAT 2002
		Energetic metabolism indicators			
n	TEC_{SA} (or TEC_{i})	**Total Electricity Consumption**: total electricity consumed in a year in the aggregate level of the whole municipality ("Societal Average, SA") or in a given in a given socio-economic sector ("i")	Expressed in megajoules (MJ)	**Flow**	ICAEN 2010
n / n-1	EMR_{SA} (or EMR_{i})	**Exosomatic Metabolic Rate:** electricity consumption per hour of human time available to the municipality ("SA") or per hour allocated to a given socio-economic sector ("i")	TEC_{SA}/THA (or TECi/HAi) Measured in megajoules per hour (MJ/h)	**Flow-Fund**	ICAEN 2010 IDESCAT 2001
n-2	TEC per ha_urban area	**Total Electricity Consumption** in urban area: electricity consumption in household, services and industrial sectors per hectare of urban area	$\Sigma TEC_{S\&G,IS,HH}/\Sigma LU_{HH, PWPS}$ Measured in megajoules per hectare (MJ/ha)	**Flow-Fund**	ICAEN 2010 GENCAT 2002
n-1	TEC per HH	**Total Electricity Consumption per household**: total electricity consumed in a year per household	TEC/number of households (HH) (MJ/HH)	**Flow-Fund**	ICAEN 2010 IDESCAT 2001
n-1	TEC per person in the HH	**Total Electricity Consumption per person living in the household**: total electricity consumed in a year per person living in a household	TEC/ person in the household (MJ/person in the HH)	**Flow-Fund**	ICAEN 2010 IDESCAT 2001
n	Balance Generation/Consumption	**Ratio of electricity generated in respect of the electricity consumed**	TEG_{SA}/TEC_{SA} Measured in %	**Flow-Flow**	ICAEN 2010
n	TEG_{SA} (or TEG_{i})	**Total Electricity Generated**: Electricity generated by all technologies (SA), or by a given type ("i")	Expressed in megajoules (MJ)	**Flow**	ICAEN 2010

Fig. 3 Dendograms of the different fund elements at different hierarchical levels. TAL total available land, THA total human activity, COL colonized land and NCL non-colonized land, PW paid work, HH household, AG agriculture, SG service and government, PS productive sectors (industry plus building and manufacturing activities) and Inf infrastructures. Asterisk Land use dedicated to Service and Government activities is not considered in our analysis because this activity usually takes place in residential areas and where it is segregated there is no a clear differentiation of it from the rest of urban area in the available data sources. This is so, because commonly a same building in core urban areas dedicates some floors to households and others to service activities



3.3 Multivariate statistical analysis to identify and characterize typologies of municipalities

Municipality typologies were built through the application of principal component analysis (PCA) (Abdi and Williams 2010) and hierarchical cluster analysis (HCA) (Härdle and Simar 2012) to a selection of the above introduced indicators for a sample of 945 municipalities[10]. PCA represents inter-correlated quantitative-dependent variables as a set of new orthogonal variables called principal components (or factors). Principal components group variables according to important patterns of similarity among them (Abdi and Williams 2010). HCA further groups the data in different clusters according to such patterns of similarity (Härdle and Simar 2012). In order to produce a meaningful clustering, we needed to select indicators relevant for accomplishing our goal of relating rural–urban characteristics and metabolic profiles of energy consumption. We selected eleven indicators (see Table 3; Fig. 3) with the aim to represent all relevant dimensions (sociodemographic structure, land-use distribution, energy metabolic profiles) and at the same time key variables related to economic dynamism (understood as employment attraction), the daily labor mobility needs, the role within the network of cities or the relative access to services (as indicated in Table 1, last column). When selecting indicators, we considered those with a high number of correlations with variables of other dimensions and dismissed those highly correlated with variables representing the same dimension. Further details

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[10] Catalonia has 946 municipalities. Barcelona, however, was left aside due to the relative big difference in size as compared with all the rest of municipalities and also due to the lack of disaggregated data about electricity consumption by neighborhoods. Its initial inclusion distorted any meaningful result. Barcelona, with 1,503,884 inhabitants in 2001 (23 % of Catalonia's population), was about six to eight times larger than the neighboring second and third most populated cities of Catalonia (Hospitalet de Llobregat and Badalona), and ten times larger than the other three province capitals of Catalonia: Tarragona, Lleida and Girona.

of applying clustering procedures based on multivariate statistical analysis can be found in Köbrich et al. (2003), Mingorría and Gamboa (2010), Siciliano (2012) and Usai et al. (2006).

Table 3. Main results of Principal Component Analysis: Factor loadings of each variable contributing to each identified factor and their eigenvalues and variability explained. Values in **bold** are those factor loadings higher than 0.4 and values underlined are those higher than 0.4 but with negative values.

	F1: "rural-urban"	**F2: "%TEChh-suburban"**	**F3: "TECper ha_urban area-industrial"**
Eigenvalue	5.77	1.57	1.11
Variability explained (%)	52.45	14.31	10.10
% accumulated	52.45	66.76	76.86
THA	**0.825**	**0.420**	0.195
$\%HA_{PWAG}$	-0.748	0.174	0.288
%Residing Workers	-0.488	**0.621**	0.399
Dependency ratio	-0.614	-0.001	**0.580**
$\%LU_{PW}PS$	**0.840**	0.019	0.042
Population density municipality	**0.808**	**0.401**	0.060
Distance to >5000 inhab. population centers	-0.773	-0.150	0.320
$\%TEC_{HH}$	-0.459	**0.754**	-0.300
TEC_{SA}	**0.871**	0.102	0.295
TEC per ha $_{\text{urban area}}$	**0.656**	-0.415	**0.443**
% of apartment buildings	**0.747**	0.215	0.112

The municipality typologies found through PCA and HCA were further characterized through the help of statistical tests for variance analysis. After conducting the normality test Shapiro–Wilk (Shapiro and Wilk 1965), all variables were found to follow a nonparametric distribution. Thus, the nonparametric test Kruskal–Wallis one-way analysis of variance by ranks (Kruskal and Wallis 1952) was used to identify statistically significant differences between municipality types, this time using all the indicators of Tables 1 and 2.

The study was conducted using data of all dimensions for the year 2001, the most recent year for which a suitable combination of population census data (IDESCAT 2001), land-use maps of Catalunya (GENCAT 2002) and related electricity consumption data are available[11]. Electricity generation and consumption data were provided by Institut Català de l'Energia (Catalan Institute of Energy, ICAEN, in its acronym in Catalan) upon request.

4. Municipality types and metabolic profiles along the rural-urban continuum

The clustering procedure based on multivariate statistical analysis derived four types of municipalities with distinct metabolic profiles regarding their sociodemographic, land-use and electricity consumption characteristics: (a) cities, (b) small villages, (c) suburban towns and (d)

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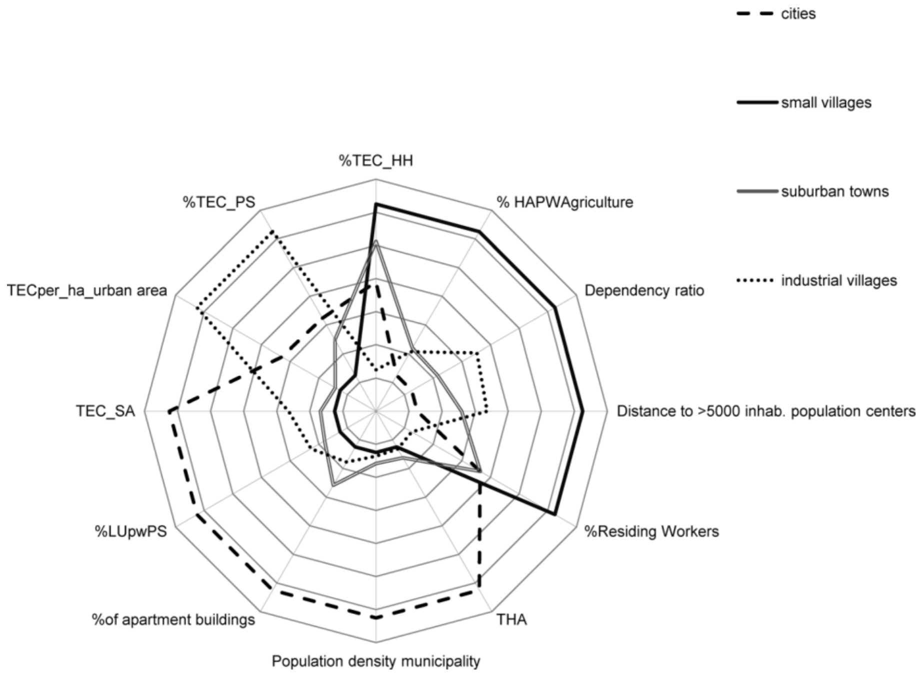
[11] Although there is demographic data available for 2007, it is not disaggregated to the required level of detail. The most recent demographic data, for 2011, while suitably disaggregated, do not include electricity consumption, and we have used the most recent, detailed land use map, which is for the year 2002. We have used the most recently available energy generation data, i.e., 2007, for the purpose of interpreting implications in our summary and conclusions.

industrial villages. These types covered the broad range of the rural–urban continuum and resulted from the grouping of the most significant indicators around three significant principal components (factors) explaining the 77 % of the variability of the sample (see Table 3). By looking at the contribution of each variable to the factors, we see that factor F1 is composed of variables whose maximization indicates either “rural” (i.e., negative variables in italics) or “urban” (i.e., positive variables in bold) characteristics.

Fig. 4. Typology profile according to the main clustering variables

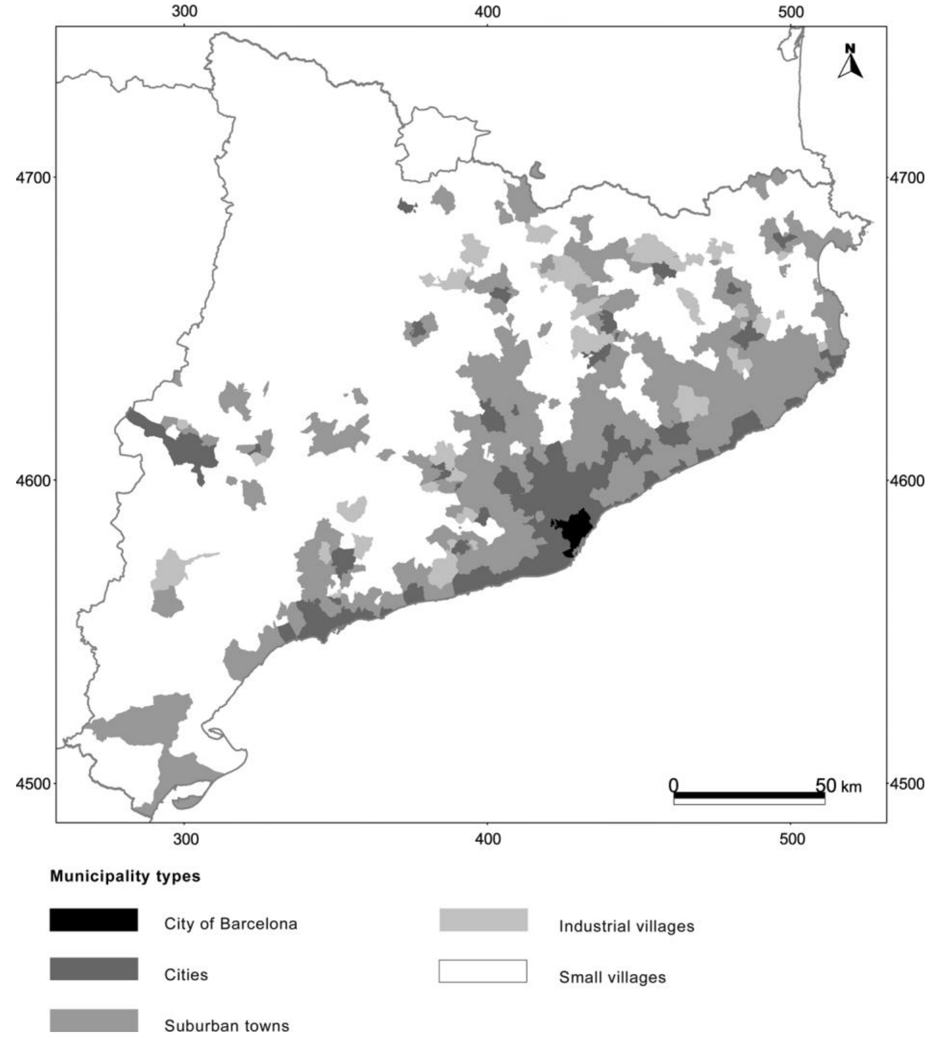


Factors F2 and F3, although less relevant in explaining sample variability, are key for understanding the formation of the other two intermediate categories. F2 illustrates the creation of suburban towns where municipalities with an intermediate size (THA), population density and share of workers living in the same village have a big share of electricity consumption in the household sector ($\%TEC_{HH}$) and a low electricity consumption per hectare of urban area ($TECper\ ha_{urban\ area}$). F3 groups the sample toward the creation of the “rural industrial village” category where villages with the rural characteristics of a high dependency ratio and a big distance to populated centers have high electricity consumption per hectare of urban area. The radar graph of Fig. 4 shows the relevant variables used in PCA and HCA and the $\%\ TEC_{PS}$ (which facilitates types distinction) to illustrate the differences between typologies according to the grouping tendencies suggested by the principal components (factors). F1 explains the tendency to go either to the upper right quadrant (indicating “rural” characteristics) or to the lower left quadrant (“urban” characteristics), forming the two extreme ideal types of cities and small villages. F2 and F3 explain the formation of the two intermediate categories of suburban towns and industrial villages by which combine typical rural–urban characteristics with MuSIASEM-based profiles of electricity consumption.

4.1. Spatial distribution of municipality types: functional urban specialization

Figure 5 shows the spatial distribution of the four municipality types throughout Catalonia. Cities, suburban towns and industrial villages are concentrated along coastal areas and around the main infrastructure corridors in the center and north of Catalonia. Small villages occupy most of the territory (67 %) in three large areas: the southern countryside, the northern mountain areas of the Pyrenees and the central and northern interstices between urban systems.

Fig. 5. Spatial distribution of municipality types along the rural–urban continuum of Catalonia. *Source:* own elaboration



This spatial distribution of municipality types has important consequences for electricity consumption. Municipalities have different profiles of electricity generation or consumption depending on their role in the urban system. Such metabolic profiles are related to functional specialization in industry, services or residential sectors.

The relative importance of electricity consumption in the paid work sectors (industry and services) is higher in municipalities with economic dynamism (employment attraction) such as cities or industrial villages. In contrast, the household sector plays a major role in electricity consumption in suburban towns and in small villages (see results of Kruskal–Wallis test, Tables 4 and 6). Geographical separation of working activities and residence is correlated with higher electricity consumption per hour of human activity and per hectare in both the employment attraction and the residential municipalities.

Table 4. Results of Kruskall Wallis test in socio-demographic variables (All variables showed a non-normal distribution under Shapiro-Wilk test. All results had 7.814 as critical value of K, a p-value <0. 0001, an alpha value of 0.05, and 3 degrees of freedom). The values highlighted in bold correspond to the typology having the maximum or minimum average values of the given indicator. Letters (^{A,B,C,D}) indicate the significantly different groups existent along the values of the sample, which aggregate typologies according significant differences.

Type	**1:cities (n=100)**		**2:small villages (n=537)**		**3: sub-urban towns (n=265)**		**4:industrial villages (n=43)**		
Variable	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	χ^2
THA	**3.07E+08**^{D}	3.77E+08	6.69E+06^{A}	9.04E+06	2.93E+07^{C}	3.03E+07	1.09E+07^{B}	1.04E+07	445.780758
% HA_{PW} AG	1.63^{A}	1.65	**35.19**^{C}	20.80	8.02^{B}	7.46	7.18^{B}	5.51	536.46
% HA_{PW} PS	44.32^{B}	14.12	29.11^{A}	14.95	46.75^{A}	14.04	**66.18**^{C}	12.35	304.15
% HA_{PW} S&G	**54.05**^{D}	13.57	35.70^{B}	15.56	45.23^{C}	12.95	26.64^{A}	11.75	191.54
Dependency ratio	41.79^{A}	5.47	**61.06**^{D}	12.07	45.27^{B}	7.36	50.56^{C}	7.84	438.70
%Residing Workers	51.79^{C}	18.00	**73.48**^{B}	14.16	51.94^{B}	16.83	32.09^{A}	13.37	357.25
%Commuting Workers	48.21^{B}	18.00	**26.52**^{A}	14.16	48.06^{B}	16.83	67.91^{C}	13.37	357.25
%Active Residents working outside	54.15^{A}	16.04	54.42^{A}	13.49	**61.65**^{B}	15.27	56.53$^{A.B}$	12.61	55.19
%HHType1: Single-person houseolds	6.59^{A}	3.43	**9.63**^{C}	3.87	7.66^{B}	5.05	7.08$^{A.B}$	2.58	139.47
%HHType2: Households without nuclear families	2.81^{A}	0.82	**4.20**^{B}	2.51	3.00^{A}	1.58	3.30^{A}	1.99	93.00
%HHType3: Couple w/o dependent children	16.87^{A}	1.64	**18.23**^{B}	4.86	17.24^{A}	3.35	16.65^{A}	3.53	22.22
%HHType4: Couple with dependent children	**60.42**^{A}	**4.93**	48.03^{C}	9.23	57.31^{B}	7.67	56.73^{B}	7.34	314.31
%HHType5: Single-parent households	**8.58**^{B}	**1.40**	8.21^{A}	3.66	7.73^{A}	2.25	7.79^{A}	3.19	19.96
%HHType6_More than one nuclear family	4.73^{A}	1.13	**11.70**^{C}	8.03	7.07^{B}	4.20	8.45$^{B.C}$	4.69	189.03
Average Number of People by HH (a) total	2.83^{B}	0.16	**2.76**^{A}	0.33	2.82^{B}	0.28	2.91^{B}	0.25	35.21
(b) HHtype2	**2.71**^{C}	0.23	2.37^{A}	0.63	2.54^{B}	0.47	2.52$^{A.B}$	0.42	96.66
(c) HHtype3	2.22^{A}	0.04	**2.38**^{C}	0.22	2.28^{B}	0.14	2.34$^{B.C}$	0.16	137.16
(d) HHtype4	4.00^{A}	0.07	**4.18**^{C}	0.29	4.05^{B}	0.13	**4.18**^{C}	0.25	122.68
(e) HHtype5	3.03^{B}	0.10	**2.91**^{A}	0.50	3.00^{B}	0.29	3.08^{B}	0.45	27.87
(f) HHtype6	6.03^{A}	0.27	5.79^{A}	1.23	5.87^{A}	0.77	5.93^{A}	0.67	7.03

Table 5. Results of Kruskall Wallis test in land use pattern variables (All variables showed a non-normal distribution under Shapiro-Wilk test. All results had 7,814 as critical value of K, a p-value <0. 0001, an alpha value of 0.05, and 3 degrees of freedom). The values highlighted in bold correspond to the typology having the maximum or minimum average values of the given indicator. Letters $(^{A,B,C,D})$ indicate the significantly different groups existent along the values of the sample, which groups typologies according significant differences.

Type	**1:cities (n=100)**		**2:small villages (n=537)**		**3: sub-urban towns (n=265)**		**4:industrial villages (n=43)**		
Variable	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	χ^2
Distance to >5000 inhab. population centers	1.32 ^{A}	1.05	**15.56 ^{C}**	12.01	5.14 ^{B}	3.73	7.34 ^{B}	6.08	538.80
TAL (ha)	2106.96 ^{A}	2463.22	**4005.06 ^{B}**	3956.82	2673.35 ^{A}	2510.73	3042.08 ^{A,B}	2827.36	54.61
% LUForest	34.47 ^{A}	20.13	54.22 ^{B}	33.98	53.09 ^{B}	27.63	**55.44 ^{B}**	30.05	34.38
% LUPWAG	28.91 ^{A}	20.49	**44.02 ^{B}**	33.10	35.52 ^{A}	26.72	38.85 ^{A,B}	27.72	18.08
% LUinf	**6.89 ^{A}**	6.65	0.35 ^{C}	1.08	1.92 ^{B}	2.62	1.61 ^{B}	2.53	303.58
% $LU_{PW}PS$ (out of TAL)	**8.48 ^{C}**	8.94	0.15 ^{A}	0.29	1.05 ^{B}	1.61	1.85 ^{B}	3.21	398.79
% LU_{HH}	**21.25 ^{C}**	12.90	1.25 ^{A}	1.54	8.43 ^{B}	9.65	2.24 ^{A}	2.27	464.28
%Nucleated urban area	65.98 ^{A}	28.13	**84.47 ^{B}**	28.12	55.27 ^{A}	33.96	64.92 ^{A}	34.65	152.73
%Dispersed rural residential	1.38 ^{A,B}	5.13	4.51 ^{A}	17.17	3.92 ^{B}	12.28	**12.01 ^{B}**	26.29	15.26
%Low density dispersed urban area	17.74 ^{B}	20.91	10.47 ^{A}	22.81	**37.46 ^{C}**	34.17	15.93 ^{A,B}	24.35	183.34
%Industrial park area (out of urbanized (paved) area)	**14.90 ^{C}**	20.45	0.18 ^{A}	1.59	2.97 ^{B}	9.23	7.14 ^{B}	17.90	264.77
Population density urban area	7992.61 ^{C}	5966.76	3076.64 ^{B}	3415.42	**2388.18 ^{A}**	2172.50	3433.08 ^{B}	4605.75	156.04
Population density municipality	**2654.75 ^{D}**	3538.52	29.27 ^{A}	36.78	205.05 ^{C}	302.49	88.15 ^{B}	144.79	494.66
%of apartment complexes in housing	**74.62 ^{C}**	15.82	20.65 ^{A}	16.54	35.05 ^{B}	20.16	26.33 ^{B}	17.91	313.53
%of single-family main homes in housing	25.38 ^{A}	15.82	**79.35 ^{C}**	16.54	64.95 ^{B}	20.16	73.66 ^{B,C}	17.91	313.53
%of second homes in housing	12.23 ^{A}	14.29	**27.06 ^{C}**	19.53	23.07 ^{B}	20.84	14.09 ^{A,B}	11.27	71.03

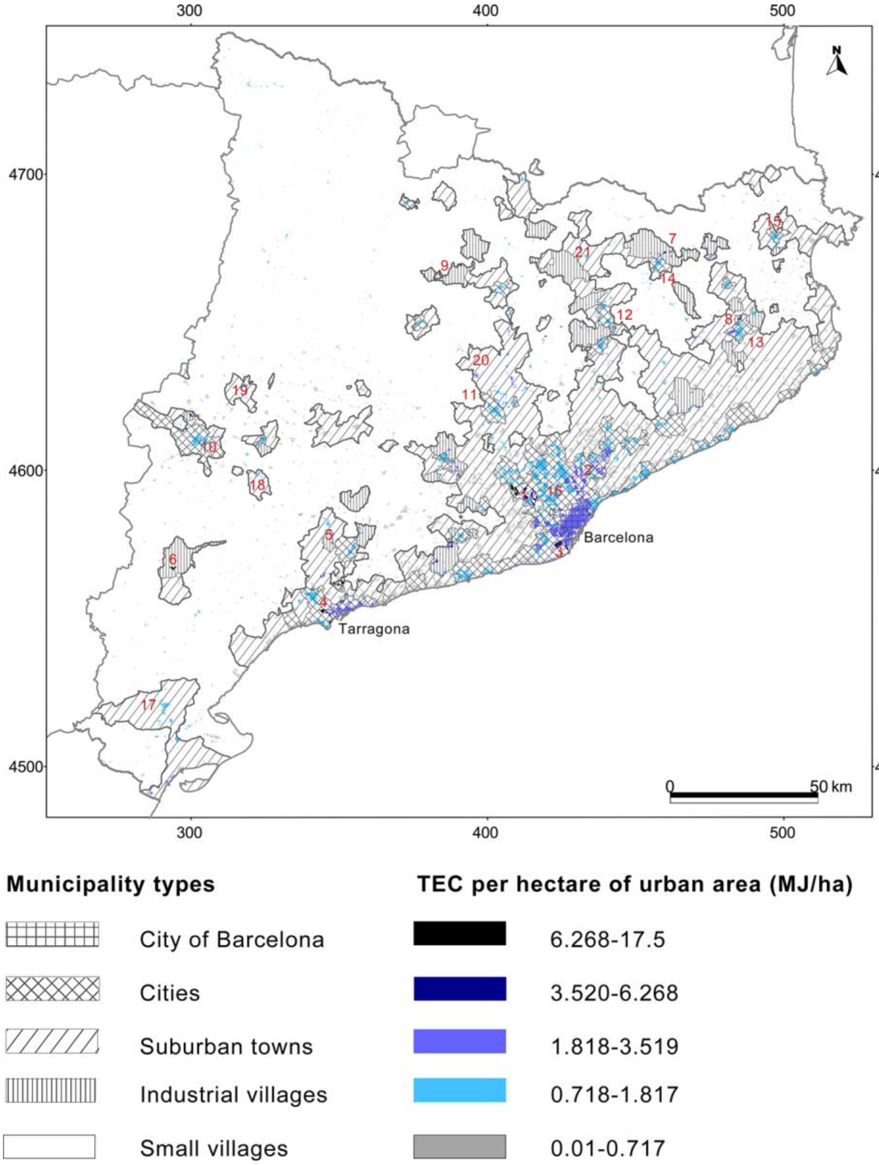
Table 6. Results of Kruskall Wallis test in electricity consumption variables (all results had 7,814 as critical value of K and a p-value <0. 0001 and an alpha value of 0.05, and 3 degrees of freedom). The values highlighted in bold correspond to the typology having the maximum average values of the given indicator. Letters (^{A,B,C,D}) indicate the significantly different groups existent along the values of the sample, which groups typologies according the significant differences.

Type	**1:cities (n=100)**		**2:small villages (n=537)**		**3: sub-urban towns (n=265)**		**4:-industrial villages (n=43)**		
Variable	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	χ^2
TEC_SA (MJ)	**7.49E+08^{C}**	8.37E+08	1.36E+07^{A}	2.21E+07	7.70E+07^{B}	9.92E+07	2.18E+08^{B}	3.71E+08	504.968764
TEC_PS (MJ)	**3.78E+08^{C}**	6.58E+08	4.36E+06^{A}	1.19E+07	3.45E+07^{B}	7.09E+07	**2.02E+08^{C}**	3.60E+08	466.423171
TEC_S&G (MJ)	**2.17E+08^{C}**	2.43E+08	4.02E+06^{A}	7.82E+06	2.08E+07^{B}	2.80E+07	9.00E+06^{B}	8.73E+06	455.823
TEC_HH (MJ)	**1.50E+08^{C}**	1.60E+08	4.27E+06^{A}	6.61E+06	2.05E+07^{B}	2.23E+07	6.06E+06^{A}	5.73E+06	458.167
%TEC_AG	0.558^{A}	2.505	**9.613^{C}**	12.331	1.255$^{A.B}$	2.174	2.508^{B}	4.786	197.517393
%TEC_PS	42.987^{C}	24.181	16.001^{A}	21.415	32.756^{B}	25.105	**83.869^{D}**	18.208	261.102
%TEC_S&G	31.425^{B}	14.013	31.184^{B}	17.974	30.378^{B}	15.692	10.125^{A}	16.791	76.6572767
%TEC_HH	25.031^{B}	13.704	**43.015^{D}**	18.539	34.358^{C}	16.746	4.752^{A}	2.608	205.274489
TEC per ha_urban area	1.608^{C}	1.316	0.422^{A}	0.541	0.522^{B}	0.487	**3.341^{C}**	3.336	299.007281
EMR_PS (MJ/h)	40.788^{C}	66.034	22.197^{A}	58.115	28.984^{B}	51.044	**206.642^{D}**	280.293	194.229269
EMR_S&G (MJ/h)	19.214^{A}	20.370	**36.109^{C}**	58.734	24.815^{B}	18.757	**38.255$^{B.C}$**	67.810	44.401618
EMR_SA (MJ/h)	3.743^{B}	5.910	1.838^{A}	1.463	2.674^{B}	1.655	**17.405^{C}**	12.595	229.764905
EMR_HH (MJ/h)	0.586^{A}	0.157	0.694^{B}	0.366	**0.818^{C}**	0.461	0.637$^{A.B}$	0.165	66.3097474
Average TEC per HH (MJ/HH)	1.32E+04^{A}	3.20E+03	1.54E+04^{B}	7.80E+03	**1.80E+04^{C}**	9.48E+03	1.49E+04^{B}	4.41E+03	66.1092883
Average TEC per person in the HH (MJ/personinHH)	4700.862^{A}	1253.269	5608.433$^{A.B}$	2914.216	**6483.005^{C}**	3773.444	5112.146^{B}	1357.920	56.7138334

4.2. Electricity consumption in working activities: specialized cities and industrial villages

High density of electricity consumption per hectare of urban area ($\text{TECper ha}_{\text{urban area}}$ (MJ/ha)) concentrates in *cities* mainly in the Metropolitan Region of Barcelona (MRB) (see numbers 1–3 in Fig. 6), Tarragona metropolitan area (number 4) but also in *industrial villages*, in the south (5 and 6) and in the north (7, 8 and 9).

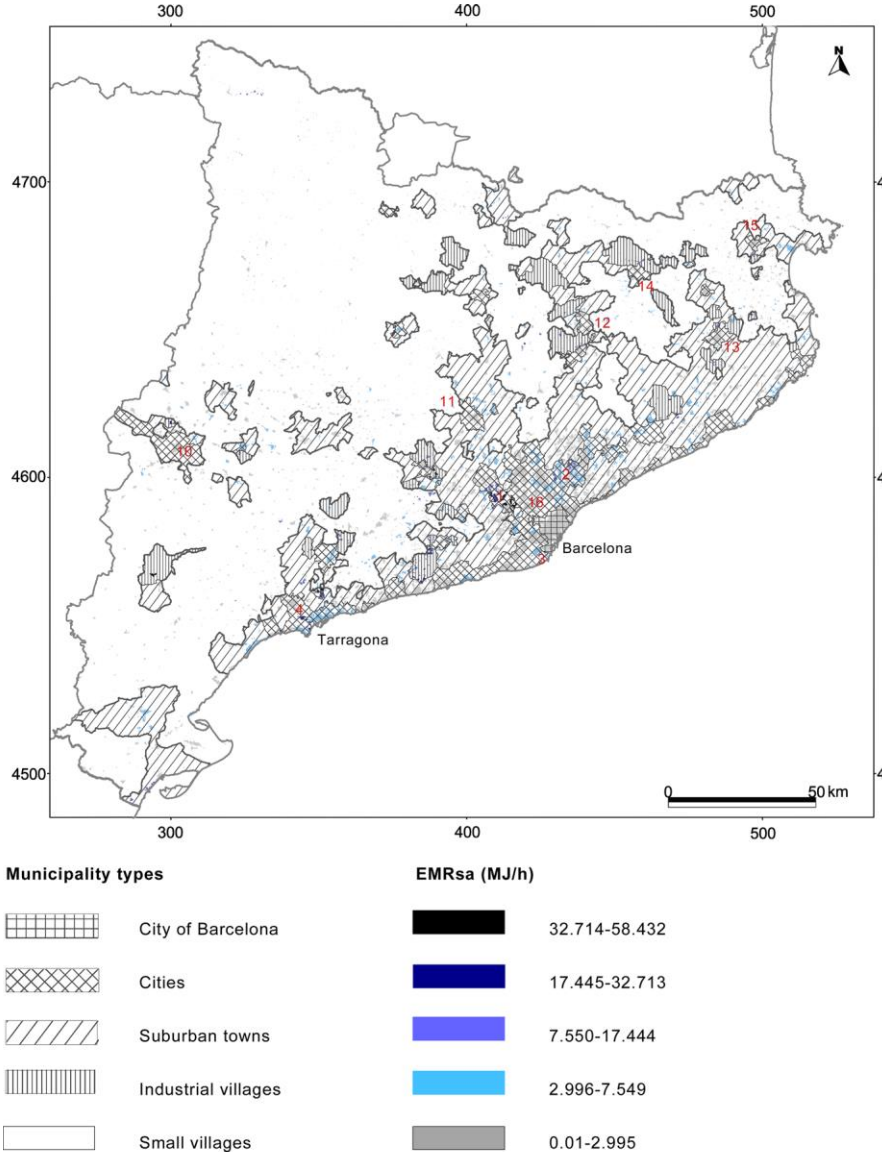
Fig. 6. Spatial distribution of total energy throughput per hectare of urban area (MJ/ha) and municipality types along the rural–urban continuum of Catalonia. Source: own elaboration. Intervals are represented following the Jiang (2012) proposed method of head/tail breaks, a classification scheme for data with a heavy-tailed distribution



Cities and *industrial villages* have higher electricity consumption at the level of whole municipality (TEC_{SA}) (see Table 6). In both cases, industry is the major consumer of electricity (see $\%TEC_{PS}$ in Table 6). Although *cities* consume more in absolute terms, both at the level of whole municipality and at the level of productive sectors, *industrial villages* consume more per hour of human activity (both in EMR_{SA} and in EMR_{PS}) and per hectare of urban area ($\text{TECper ha}_{\text{urban area}}$). As industrial employment attractors (66 % of activity), but with lower proportions of land dedicated to industrial parks, they consume electricity almost entirely through a highly intensive industrial sector (accounting for the 84 % of TEC_{SA}) (see Tables 5 and 6).

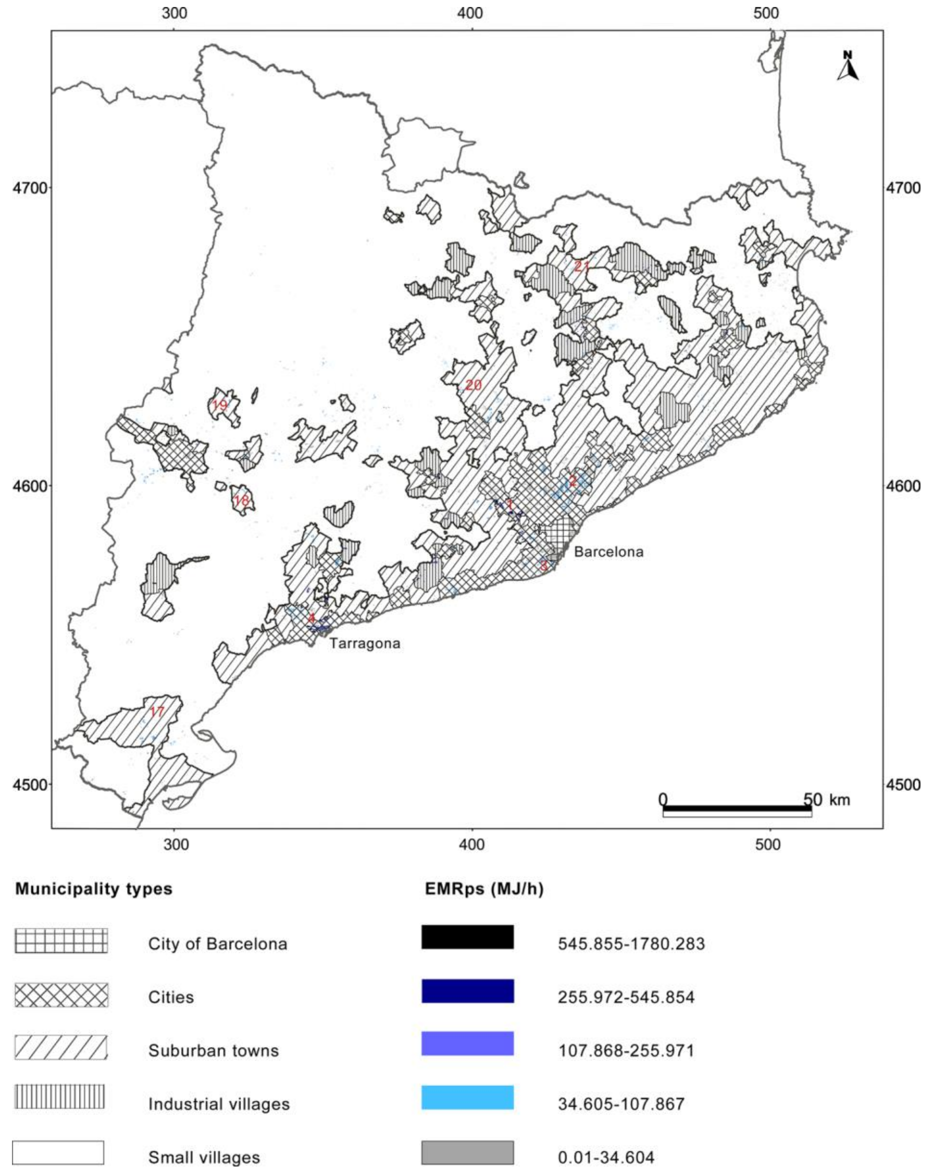
The high consumption of *cities* is related to their size and their specialization. *Cities* have contrasting values in energy consumed per hour of activity (EMR_{SA}) (see Fig. 7), depending on their functional specialization.

Fig. 7. Spatial distribution of energy metabolic rate (MJ/h) at the level of the whole municipality (EMR_{SA}) and municipality types along the rural–urban continuum of Catalonia. Source: own elaboration. Intervals are represented following the Jiang (2012) proposed method of head/tail breaks, a classification scheme for data with a heavy-tailed distribution



Cities in the northern part of the MRB, “Comarques Centrals” and “Camp de Tarragona” (see Figs. 1, for area location, and values around numbers 1–4 in Fig. 7) are more oriented to industry and have higher energy metabolic rates (6,402 ± 8,712 MJ/h of human activity, on average), mainly explained by a higher proportion of industrial workers and electricity consumption in productive sectors (high EMR_{PS}) (see values around numbers 1–4 in Fig. 8). *Cities* located along the coastal areas and urban centers in the countryside are more oriented to services and have lower EMR_{SA} (1,895 ± 0,771 MJ/h, see numbers 10–16 in Fig. 7). “Industrial cities” consume a lot of energy per hectare due to their industrial parks (see numbers 1–4 in Fig. 8). “Service cities,” on the contrary, do so, because of high density of population and service activity. They are big compact cities with high concentrations of apartment buildings which have intermediate densities of electricity consumption per hectare but comparatively low intensities of consumption, per hour of human activity (see the contrast between numbers 10–16 and Barcelona city in Figs. 6 and 7).

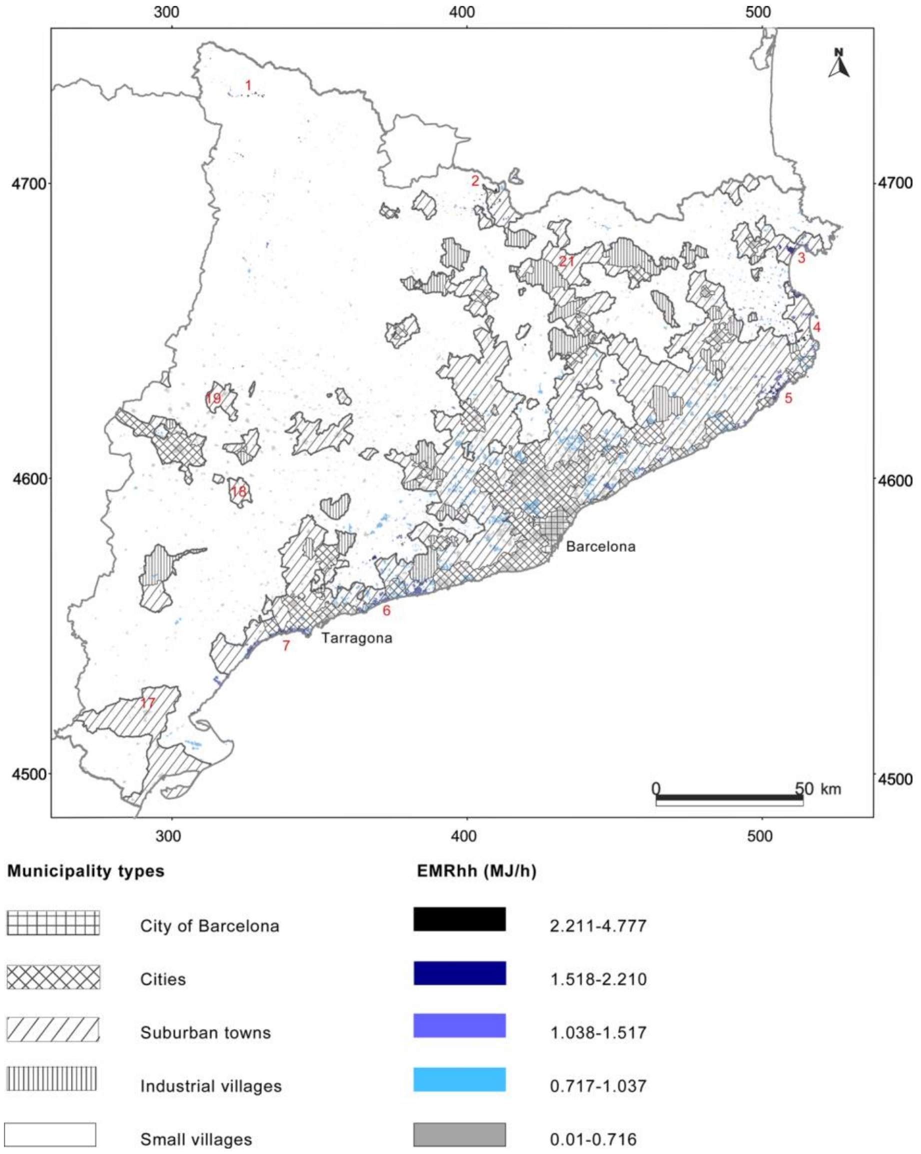
Fig. 8. Spatial distribution of energy metabolic rate (MJ/h) at the levels of the productive sectors (EMR$_{PS}$) and municipality types along the rural–urban continuum of Catalonia. Source: own elaboration. Intervals are represented following the Jiang (2012) proposed method of head/tail breaks, a classification scheme for data with a heavy-tailed distribution



4.3. Electricity consumption in the household sector: suburban towns and small villages

Suburban towns and *small villages* consume less electricity as compared to *industrial villages* and *cities* and have a distinct complementary metabolic pattern (see Table 6). They tend to play a residential role, sending workers to *cities* and *industrial villages* (%Active Residents working outside in Table 4). Where people live and work in the same village (%Residing Workers in Table 4), total municipal electricity consumption (Table 6) tends to be lower and the share attributable to the household sector ($\%TEC_{HH}$) higher. *Suburban towns* and *small villages*, in comparison, consume more electricity per hour spent in the household (EMR_{HH}) and less per hectare of urban area (TEC per $ha_{urban\ area}$) than the other two types. While the average number of people per household is similar across municipality types, *suburban towns* have the highest average consumption of electricity per household and per person living in the home. High EMR_{HH} and low TEC per $ha_{urban\ area}$, thus, seem to be related to a lifestyle characterized by consumerism in low-density urban sprawl (37 % of urban area of this type, see Table 5).

Fig. 9. Spatial distribution of energy metabolic rate (MJ/h) at the level of household (EMR_{HH}) and municipality types along the rural–urban continuum of Catalonia. Source: own elaboration. Intervals are represented following the Jiang (2012) proposed method of head/tail breaks, a classification scheme for data with a heavy-tailed distribution



A closer look at the spatial distribution of EMR_{HH} (see Fig. 9) reveals that further specialization takes place among *suburban towns*, depending upon where they are located within the urban system. The highest energy consumption per hour spent in the household takes place in the northern mountain areas (numbers 1 and 2 in Fig. 9) and in coastal areas to the north

("Costa Brava" in "Comarques Gironines", see values around numbers 3–5) and to the south ("Costa Daurada" in "Camp de Tarragona," values around numbers 6 and 7). *Suburban towns* in these areas are touristic, with high income per capita and, on average, more than 60 % of the urban land is low-density urbanization with a high proportion of single-person households (16 %) and of second homes (60 %). There is scant industrial activity and most of the population works in services. Households in such high-income, touristic areas consume, per hour of activity, the triple the electricity of *cities* or *small villages* in the southern countryside.[12]

Suburban towns play a different role in the southern countryside, where they serve as local capitals and economic centers, or where they form part of the industrial fabric of the center and north. In these cases, they consume half as much electricity per hour in the household sector (see numbers 17–21 in Fig. 9) and have higher-density urban areas, less urban sprawl and lower percentages of second homes. Their human time is dedicated less to services and more to industry, which explains their higher energy throughput per hectare and higher EMRPS compared with the touristic and high-income towns and the commuter dormitories surrounding metropolitan centers (see numbers 17–21 in Figs. 6 and 8).

Small villages reproduce the influence marked by the specialization of the nearest suburban towns. Villages closer to high-income and touristic towns, for example, have more urban sprawl, more percentage of second homes and more service activity. Consequently, they have higher energy consumption rates per hour and per hectare, as compared to more agrarian-oriented small villages of the southern countryside which are among the lowest energy consumers per hectare and per hour of human activity.

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[12] Since detailed data about differences in the number and use of electric appliances at the level of municipality are not available in IDESCAT 2001, we cannot assess their influence in explaining this substantial difference of EMRHH in coastal touristic areas. However, our results show statistically significant differences between higher incomes, higher proportion of single-person households, higher proportion of second homes and the lower urban densities in touristic and coastal suburban towns. Higher incomes and higher proportions of single-person households in these municipalities seem plausible explanations. As will be explained subsequently, the higher proportion of single-person households correlates with higher needs for appliances for more people who live alone. The higher proportion of second homes, however, does not necessarily explain the higher consumption, and it could even entail some bias in the results. People on vacation are not registered in the census as permanent dwellers and could not be accounted in the calculation, leading us to attribute the consumption of both permanent dwellers and vacationers, to only the dwellers. However, we think that this bias is distributed all along the sample. All municipalities with second homes will bear the same potential bias. Regarding lower urban densities, other studies, such as Tello (2005), have shown how the electricity consumption per capita, the number of cars per capita and the water consumption per capita are strongly correlated with low-density urbanization. This helps to explain the high level of electricity consumption in the household sector.

Table 7. Results of Kruskall Wallis test in electricity generation variables (correlated results are found in installed capacity) (all results had 7.814 as critical value of K and a p-value <0. 0001 and an alpha value of 0.05, and 3 degrees of freedom). The values highlighted in bold correspond to the typology having the maximum or minimum average values of the given indicator. Letters (^{A,B,C,D}) indicate the significantly different groups existent along the values of the sample, which groups typologies according the significant differences.

Type	**1:cities (n=100)**		**2:small villages (n=537)**		**3: sub-urban towns(n=265)**		**4:industrial villages (n=43)**		
Variable	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	**Mean**	**Std.dev.**	χ^2
Balance Generation/Consumption in % (2001)	100.812^{B}	826.385	**1778.818^{A}**	11615.231	852.691^{A}	11462.916	117.626$^{A.B}$	514.741	26.4146825
TEG (MJ net prod.) (2001)	1.81E+08^{C}	6.76E+08	3.30E+07^{A}	1.69E+08	**3.62E+08^{B}**	3.98E+09	1.75E+08^{C}	5.03E+08	94.0733563
Combined heat and power (CHP) (MJ net prod.) (2001)	1.07E+08^{C}	3.22E+08	2.01E+06^{A}	1.67E+07	6.75E+06^{B}	4.01E+07	**1.54E+08^{C}**	4.90E+08	194.040359
Renewable generation (MJ net prod.) (2001)	**2.10E+03^{B}**	1.62E+04	1.03E+06^{A}	1.69E+07	1.11E+05^{A}	1.62E+06	0.00E+00^{A}	0.00E+00	32.651
Fotovoltaica (MJ prod.neta) (2001)	**2.10E+03**^{B}	1.62E+04	0.00E+00^{A}	0.00E+00	5.01E+02^{A}	4.81E+03	0.00E+00^{A}	0.00E+00	51.651
Wind power (MJ prod.neta) (2007)	0.00E+00^{A}	0.00E+00	1.02E+06^{A}	1.69E+07	1.11E+05^{A}	1.62E+06	0.00E+00^{A}	0.00E+00	1.02*
Balance Generation/Consumption in % (2007)	125.03^{C}	840.43	**695.79^{A}**	5054.19	1717.81^{B}	25159.90	70.86$^{B.C}$	162.86	48.07
TEG (MJ net prod.) (2007)	**4.26E+08^{C}**	2.29E+09	2.71E+07^{A}	1.33E+08	3.33E+08^{B}	3.68E+09	1.73E+08^{B}	5.67E+08	98.18
Combined heat and power (CHP) (MJ net prod.) (2007)	9.16E+07^{A}	3.11E+08	1.43E+06^{A}	1.45E+07	6.73E+06^{B}	5.30E+07	**1.56E+08^{B}**	5.59E+08	116.102
Renewable generation (MJ net prod.) (2007)	2.38E+05^{C}	4.72E+05	2.18E+06^{A}	2.37E+07	**2.39E+06^{B}**	3.71E+07	3.20E+05$^{A.B}$	1.62E+06	118.010
Solar Photovoltaic (MJ prod.neta) (2007)	**2.38E+05^{C}**	4.72E+05	6.40E+04^{A}	3.65E+05	9.99E+04^{B}	3.36E+05	3.20E+05$^{A.B}$	1.62E+06	133.574034
Wind power (MJ prod.neta) (2007)	0.00E+00^{A}	0.00E+00	2.11E+06^{A}	2.37E+07	2.29E+06^{A}	3.71E+07	0.00E+00^{A}	0.00E+00	2.72*

* The statistical test was deploying no significant difference between typologies of wind energy generation due to the low amount of wind farm in operation at the date of the analysis, all being located in small rural villages

4.4. Electricity generation

This spatial segregation of functions along the urban system is fed by a centralized and concentrated system of electricity generation. Power plants in southern *suburban towns* and northern *small villages* generate around 1,000 times more electricity than these municipalities consume. Although there is, on average, some balance between generation and consumption in *cities* and *industrial villages* [mainly due to the distribution of fossil fuel-based combined heat and power (CHP)] (see Table 7), summing up all types of electricity generation, *suburban towns* generate twice as much electricity as *cities* and *industrial villages*. Renewable electricity generation in 2007 was ten times higher in *small villages* and *suburban towns* than in *cities*. Although from 2001 to 2007, renewable energy supply grew in the high-consuming *industrial villages*, it is still seven times lower than in *small villages* and *suburban towns*. Renewable generation in *cities* and *industrial villages* is entirely photovoltaic, while wind energy is generated only in *small villages*.

5. Distributed energy generation versus functional urban specialization: on the need for qualitative changes

The preceding review of four types of Catalan municipalities has allowed us to identify relationships between the demographics, economic activity, mobility and electricity consumption of different communities, distributed across the urban system. Differences found in metabolic rates relate to the role undertaken by municipality types, illustrating current urban functional specialization[13] (Duranton and Puga 2005) and spatial segregation of working and residential activities. We find that segregation of activities between cities and industrial villages, where the paid work takes place, and suburban towns and small villages, where the workers reside, correlates with high speeds and densities of electricity throughput. As Lobo and Baena (2009) have suggested, we find that areas with faster growth and more economic dynamism, whether in residential or industrial activity, located at the edge of urban sprawl, concentrate higher energy dissipation.

On the other side of the coin, our analysis shows an unbalanced pattern of electricity generation, concentrated in towns close to the municipalities with the lowest consumption, in the southern countryside. In both the paid work and the household sectors, metabolic rates of electricity consumption are higher in the north and center of Catalonia. The current distribution of electricity consumption depends upon large centralized grids, incurring non-negligible losses through transmission and distribution. The high electricity consumption of northern industrial villages and suburban towns suggests that these areas should be prioritized for the development of renewable energy projects, both on efficiency grounds and with reference to environmental justice (Ortega and Calaf 2010), which suggests that high consumption areas should bear the brunt of generation. This had begun to happen, with an increase in photovoltaics in industrial villages between 2001 and 2007. However, merely generating closer to consumption does not address the intensity differential that we observed, which appears to be related rather to the segregation of residential and productive activities. Co-occurrence of residence and work can, on

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[13] Technological progresses in transport and telecommunications have made it less costly for firms to separate their production facilities from their management headquarters. Manufacturing sites are clustered in smaller but more numerous cities, while business and services centers are few and large cities that concentrate abundant business service employment (Duranton and Puga 2005).

balance, be expected to reduce electricity consumption and would also reduce mobility-related energy demand.

Our data suggest that urban planning targeted toward a structural qualitative change is needed, if overall energy consumption is to be reduced. Our results confirm that dispersed urban land use, associated with larger houses and more detached units, which consume more energy (in heat and electricity), is correlated with higher-intensity electricity consumption (Ewing and Rong 2008, Tello 2005). Suburban towns, with higher per capita income and greater degrees of urban sprawl, are consuming more electricity per hour of activity. Tello (2005), in diagnosing the environmental problems related to urban sprawl in the Metropolitan Region of Barcelona, shows similar results, with correlations between low-density urbanization and higher electricity and water consumption per capita and higher number of cars per inhabitant. Suburban towns are also the municipalities where there are a higher percentage of single-person households, which are growing in number regionally in Catalonia and in Spain (Gamboa 2009; Ramos-Martín et al. 2009) and elsewhere (Liu et al. 2003; Williams 2007). Although economies of scale are less pronounced in electricity than in natural gas consumption for heating (Brounen et al. 2012), our data suggest that the more people live alone and the higher the proportion of detached houses in a municipality, the more electricity will be consumed. The increasing number of appliances in single-person households, no matter how efficient they are, lies behind the reported findings that efficiency gains are offset by demographic changes in household size and household area (detached households in urban sprawl areas) (Freire 2011; Gram-Hanssen et al. 2004; Kaza 2010), which can be attributed to the rebound effect or Jevons Paradox (Giampietro and Mayumi 2008; Jevons 1866).

Our results also suggest that urban planning measures should be aware of the risk of mistakenly supporting the promotion of "smart cities" oriented to services (Domingue et al. 2011). While service cities consume less electricity per hour of activity, such measures would be once again geographically externalizing high-energy throughput agricultural and industrial activities. Instead, our data suggest that low-energy future urban planning should focus on balancing the spatial distribution of land- and time uses.

Recovering Howard's (1898) (1985 [1898]) idea of promoting the creation of polycentric urban systems (Catalán et al. 2008), composed of networked compact medium-size cities, towns and villages, Catalonian society could aim to relocate existing nodes of dense electricity consumption toward a diversified collection of centers. Promoting diversified economic activity, including concrete work opportunities in the agrarian sector, could help to revitalize rural areas and balance out rapid urban growth. The recovering of integral management of the agroforestry mosaic can be expected not only to provide new opportunities for young people who currently are moving to the cities but also to represent a chance to more efficiently distribute electricity consumption in rural areas. In keeping with Tello et al. (2013), our results suggest that increasing local, decentralized renewable energy supplies in Catalonia has the potential to facilitate the integration of renewable energies within wider efforts to recover the region's agroforestry mosaic.

However, polycentric compact medium-size cities and revitalized rural areas should not be confused with urban sprawl and the "consumption countryside," where urban residents consume the amenities of an "untouched" rural landscape (Marsden 1999). Urban sprawl diffuses urban lifestyles to a very interrelated network of small villages promoting a "liquid rurality" where commuting is the principal mode of integration into labor markets (Camarero

2009). Part of the current blurring of traditional boundaries of rural and urban areas has been the result of this urbanization of the countryside. In our study, we have found that co-occurrence of work and residence is correlated with lower intensity and lower overall electricity consumption. Urban and spatial planning for a renewable energy transition, thus, should promote such co-occurrence, transforming both city and countryside together.

Our results and methodology can be used, when combined with participatory and multicriteria decision support methodologies (Munda 2008) to assess the plausibility and energetic sustainability of different scenarios in land-use planning and urban growth in Catalonia. For example, because it illustrates that urban growth centered and limited to the outskirts of medium-size, compact and multi-functional towns would entail lower energy consumption than exacerbating the urban sprawl of low-density and mono-functional conurbations for commuter's residence. This assessment would help society to reflect upon the energy saving potential of qualitative changes in the spatial distribution of demographic structures.

6. Conclusions

In the preceding pages, we have characterized a typology of municipalities based on a combination of demographic, land-use and human activity data and associated energy metabolic profiles. We found that electricity consumption is related to functional specializations in roles undertaken by different types of municipalities within the urban system of Catalonia, Spain. Municipality types were found to have differing household and paid work sector metabolic profiles, dependent upon whether they serve mainly an industrial, services or residential role. Segregation between work activity and residence was found to be correlated with increases in both overall electricity consumption and in both its rate (per hour) and density (per hectare). In contrast, we found an inverse correlation associated with higher the coincidences of paid work activity and place of residence in a municipality, which corresponded with increasingly lower electricity consumption per hectare and per hour of human activity. This suggests that future energy system planning should pay attention not only to where new generation facilities are located but also to where and how economic activities and residential settlements are distributed across a region.

Potential further applications of the approach presented here might include: referencing additional data on heating and transport energy demand, which could provide insights regarding how overall demand can be reduced; or extending the boundaries of the metabolic profiles into other spatial dimensions relevant for sustainability, based on data concerning, for example, water supply and consumption or waste generation. An update of the present analysis, using data from after the 2007 financial crisis also seems recommendable, as current energy demands in Catalonia have certainly been impacted. Future research could also, for example, examine how smart-grid installations might be used to help gather anonymous disaggregated, geo-referenced data on energy consumption by household type at the level of municipality. Our study suggests that the availability of such data could be quite useful for better understanding how household sector composition, urban densities, urban hierarchy and energy consumption are related.

Our study began with the presumption that energy generation will be more distributed in the coming energy scarce future. Our results suggest that this will need to be complemented by structural and social transformations that coordinate the energy system with spatial planning. In particular, a distributed generation plan that fails to reverse the spatial segregation of residential and work activities, which is correlated with not only higher transport demands, but also higher electricity consumption, seems unlikely to reduce overall consumption and maximize efficiency of distribution. Living in a society based on renewable energy requires new thinking concerning overall energy supply and individual demand. However, this is not enough. Careful attention to social and demographic transformations is needed, and cumulative energy demands need to be adjusted to the spatially differentiated capacities and constraints of a distributed energy system.

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