Journal of Urban and Environmental
Engineering, v.12, n.1, p.128-146

ISSN 1982-3932
doi: 10.4090/juee.2018.v12n1.128146

Journal of Urban and
Environmental Engineering

www.journal-uee.org

PARTIAL ENERGY MATRIXES ON URBAN SCALE FOR TRANSPORTATION: A CASE STUDY OF METROPOLITAN AREAS OF BORDEAUX, CINCINNATI AND CURITIBA

Neilor de Carvalho Paes[*] and Aloísio Leoni Schmid

Department of Civil Engineering, Federal University of Paraná, Brazil

Received 21 November 2017; received in revised form 1 July 2018; accepted 10 July 2018

Abstract: Energy consumption and its economic, social and environmental effects in cities is a relevant issue of growing concern that requires better tools for assessment and measurement. In this context, the aim of this article is to explore the concept of a city energy matrix, with focus on the transportation sector, to support political decision-making. Partial (only transportation-related) energy matrixes are presented for three cities: Bordeaux (France), Cincinnati (USA) and Curitiba (Brazil), using an energy accounting method. The study considered consolidated energy consumption data of the conurbation area around each city. This information allowed the elaboration of inferences made from matrixes, which involved urban population and economic indicators, as a strategy to understand the relationship between urban characteristics and energy consumption. Results obtained were compared to information available in the literature. National and local influences as city size, spatial structure, economic development and access to data in the final matrixes are reported. Relevant theoretic issues to be further explored are the adequacy of the political boundaries and the actual geographic distribution of energy consumption of trucks, trains and airplanes connecting the city to other regions.

Keywords: Energy Outlook; Energy Efficiency; Conurbation; Bordeaux; Cincinnati; Curitiba.

---

[*] Correspondence to: Neilor de Carvalho Paes, Tel.: +55 41 99975 1556. E-mail: neilor.paes@gmail.com

INTRODUCTION

Since the United Nations Conference on Environment and Development (UNCED), Rio-92, the use of limited resources has not only been described in more detail than ever, but also attracted the attention of researchers, interested in modeling it in order to explain its behavior. Much of the effort is related to non-renewable energy resources and their scarcity on Earth. As a cornerstone of development and national security for any country, energy is a perennial concern for the world population. In this century, the urbanization process continues as a global tendency, reaching 52.6% of global population, and even higher rates in some countries, as 86.3% in France, 82.6% in the USA, and 84.9% in Brazil (WORLD BANK, 2012).

In the dynamics of energy consumption, there is a special concern for conurbation in metropolitan areas and its relationship to energy consumption. In that context, the *Ignis Mutat Res - penser l'architecture, la ville et les paysages au prisme de l'énergie* program was launched in 2012 as an initiative of the French Government. One of the endowed research projects was based on a team involving three universities: *École Nationale Supérieure architecture et les Paysages*, in Bordeaux (France); the University of Cincinnati (USA) and the *Universidade Federal do Paraná* in Curitiba (Brazil). The entire multidisciplinary project was under the scientific responsibility of Professor Kent Juan Fitzsimons (Bordeaux), who addressed the rising issue provided by the trinomial: ‘energy – metropolis – mobility’.

This article presents the sub-project of building city energy matrixes for the involved metropolitan areas of Bordeaux, Cincinnati and Curitiba, taken as case studies. Energy matrixes are inventories conducted by countries taking into consideration the production and consumption of energy, sorted by energy source and activity. For decades, this tool has been used to help nations to develop their energy planning and support decision-making, also allowing timelines and international comparison. Energy matrixes are commonly built in either a national or a regional scale. An approach in the urban scale is not usual, although an energy matrix could explain complex mechanisms of a city. This article presents the research subtask with the objective of exploring energy matrixes in the urban scale. The study is limited to a single end use of energy: transportation.

Background and literature review

Research on energy consumption in cities has been conducted in different ways. Kenworthy and Laube (1996) compiled data on transportation-related energy consumption. One conclusion was that the use of cars in cities is higher in American and Australian cities as a primary effect of a lower density of urban population in those continents. A lower density suggests a larger number of channels for automobiles, which in turn leads to their use. Denser cities require less displacement; therefore, there is a smaller dependence on the automobile. There is also a trend towards the sense that the greater the use of automobiles, the greater the available infrastructure for vehicles. On the other hand, the denser the city, the greater the use of public transport: better public transportation systems are made viable and there is a lower dependence on automobile. At the end, the authors presented strategies towards a more sustainable transportation system, which are divided in four parts: guidelines for land use, objectives for private transportation, public transportation goals and non- motorized transportation goals. All of these are strategies that promote the use of public transportation instead of automobiles.

An analysis correlating urban sprawl and car use (Cameron *et al.*, 2003) reached similar conclusions. According to that study, the larger the area occupied by a city, the greater the tendency to car use. Thus, an appropriate policy is the promotion of compact cities, encouraging smart growth (as in the U.S.) and urban consolidation (as in Australia), in order to prevent urban sprawl. In the analysis of several studies that used primary sources, such as government statistics, Kuhnimhof *et al.* (2012) concluded that there was a decrease in the use of cars by young people (18 to 29 years) in Germany in the last decade. According to the authors, two main causes were the increased use of multimodal, especially among those who had cars, and a decrease in car ownership among young adult men, reduced to the point that there are no differences between young men or women.

In the context of the energy crisis that hit California in the early 2000s, Ghanadan and Koomey (2005) created scenarios of energy consumption in California, based on data of government agencies. Growth rates for several variables were estimated according to government, specialists and problem solvers. Four scenarios were modeled in the LEAP system (Long-range Energy Alternative Planning), developed by the Stockholm Environment Institute (SEI). Besides BAU (business-as-usual), scenarios were curiously named as Split Public, Golden State and Patriotic Energy Independence, representing the main idea beyond considerations made.

Yophy, Jeffrey and Chien - Yuc (2010) undertook a study on the long-term forecast of demand and supply of energy in Taiwan by means of a holistic analysis of energy consumption for 2030, based on data from official statistical balances. Five scenarios were considered. Given the area of the country, of 36.000 km^2, the analysis approaches the city scale.

Shabbir and Ahmad (2010) considered the urban scale a study on pollution and energy demand by the transportation sector in Rawalpindi and Islamabad

(Pakistan), using the LEAP model, from the Stockholm Environmental Institute. Several existing transportation choices for passengers were considered. From official data on the number of vehicles, distances travelled by them and their energy efficiency, authors looked for a better understanding of the interactions between urbanization, transportation, energy and emissions. Authors underline that in the context of a typical medium-sized city in a developing country, the number of vehicles reduces the performance of transportation systems, resulting in lower average speed, higher fuel consumption, higher accident rates and higher emissions of greenhouse gases (GHG). One of the scenarios considered the possibility of a population decrease.

Zhou *et al.* (2013) studied how deployment scenarios of urban settlements influence energy consumption on the island of Xiamen, China. Modeling was made through TRANUS (an integrated land use and transport modelling system), which had been adopted in other cities such as Baltimore, Sacramento, Osaka, Caracas and Bangalore. Five urban sectors were considered: activities, traffic analysis, residents, transportation modal and road network. Three scenarios were built: business-as-usual (BAU), transition of settlement morphology (TSM) and transition of settlement morphology with policies (TSMP). In the last scenario, policies comprise measures in three areas: transportation (prioritizing public transportation, building a four-stage road network and building walkways and cycling roads); land use (controlling the industrial land an improving the land use mix, and economy (taxation on cars and subsidies for bus operation). Results showed that the differences in average travel distance and time, distribution of car use, as well as changes in land use, in places of residences and employment explain the differences in energy consumption and CO_2 emission in the different scenarios. TSMP led to more dispersed residential areas and jobs, along with the diversification and intensification of land use. While economic and transportation policies discouraged the increased use of cars, they reduce the average number and length of offsets. This study demonstrated the great impact of urban policies and the morphology of settlements in China, which extends to many other situations in the country and even in other developing nations.

Le Néchet (2012) handled the relationships between urban structure, mobility and energy consumption in a study of 34 European cities, where reliability and availability of data were the key to a multidimensional analysis. The author compared traditional socioeconomic and geographic indicators used to characterize a city and morphological indicators. First group was based on a database established in 2006 on 2001 data by UITP (*Union Internationale des Transports Publics*) about mobility, and second was based on a set of morphological indicators computed for the same urban boundaries from raster density provided by the EEA (European Environment Agency). The author listed indicators of urban structure based solely on the population density of the database provided by the EEA. Among indicators like population, density, GDP (Gross Domestic Product), car ownership and the rate of the public transportation mesh and the highway system, a correlation was found between energy consumption on transportation and GDP.

Le Néchet (2012) concluded that the rate of car ownership is related to the increase in energy consumption; dispersion of the inhabitants in the space appears to be less energy efficient, *ceteris paribus*. The presence of entropy in that model correlated to energy consumption; this illustrates the characteristic diffuse urbanization observed in European cities, where an endless, urbanization requires a greater amount of energy used for moving around in it. Moreover, the author stated that polycentricity is inversely proportional to energy consumption per capita in transportation. The author makes the remark that “the debate on which urban forms should be encouraged in the context of sustainable cities remains fully open” as the energy consumed per inhabitant due to transport is partly related to attributes of urban form, being larger in rich, motorized, sprawled, diffused and polycentric cities. Two final remarks by the author are: “the multidimensional approach of the determinants of mobility must be accompanied by a multidimensional reflection on the city we wish to develop for tomorrow” and “in practice, urban policies cannot be decided using an ‘all things being equal’ approach, which stresses the need to further study the complex relationships between urban form and mobility”.

The studies mentioned converge to the view that the car dependence distinctive of the industrialized world and extends to developing countries, where it can take on even greater proportions. The implications of that dependence appear in energy consumption and air pollution, which are directly related to the combustion of vehicle fuels in urban centers. However, that common conclusion was obtained in studies with quite different and distinct approaches. This is due to the large amount of variables that directly affect energy consumption, especially in urban transportation. As case studies present a diversity of geographical, political and economic conditions, such variables grow more evident in some case studies than in others. Different studies were based on government data on fuel sales, which is not identical to a geographically-referred energy consumption. There is indeed not possible to refer a vehicle energy consumption to a single point, as energy consumption occurs along with the displacement. A bottom-up strategy would be both exact and impractical. Conversely, a top-down strategy is more feasible, despite the uncertainties implicit to it.

METHOD

Rationale

In the present *Ignis Mutat Res* research program the following division of work was adopted: the French team addressed social issues, the American team the design issues and the Brazilian team set the focus on quantitative data. One of the main contributions of this research was to make available data on energy consumption more intelligible. Nevertheless, working with cities from different countries, cultures and, especially, different views and definitions of some concepts showed that the data collection process is affected by a lacking data homogeneity, lack of some specific information, political-administrative differences and technical discrepancies.

A partial energy matrix on transportation was obtained for each metropolitan area. Due to above mentioned situations, authors were reluctant to compare case studies with each other – accepting a current view of the case study, as defined by YIN (1994), as a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence. However, authors could notice that case particularities go further than data availability. Even if it would be possible to build the same indicators and place the three metropolitan area side by side, interpretation issues would remain, as a set of quantitative parameters would not capture the whole meaning of each city, the role played by each city in the respective national and regional economies.

The problem of building energy matrixes or outlooks in the urban scale starts at the definition of what is, in economic terms, a city and what is a metropolitan area. Next, it requires the convention of geographically referred energy consumption. In this sense, the present work is an exploratory.

The study was developed from the central problem: "what are the partial energy matrixes of Bordeaux, Cincinnati and Curitiba?" In this sense, authors presuppose that urban energy matrixes can be inferred from a wider scale: regional or national. This requires the elaboration of an energy inventory, in order to obtain matrixes for a closer area to the metropolitan area, and, then, compare the ratios of available urban indicators and energy consumption.

Cities of Bordeaux, Cincinnati and Curitiba

Bordeaux

Located in the French Southwest, near to the Atlantic coast, it has about 240 000 inhabitants (1 100 000 in its metropolitan area). Bordeaux is also an important seaport, fifth greatest in France, being Capital of the Aquitaine Region as well as of the Gironde Department. A great wine producer, Gironde has in Bordeaux its main spreader. Nowadays, it spotlights technology, aerospace and defense industries, being in these fields the second largest Department in France.

Besides, the tertiary sector employs the majority of the population, and tourism is a relevant economic activity. In this study, authors considered as metropolitan area *La Communauté Urbaine de Bordeaux* (CUB), which is composed by 28 communes.

The transit system has 44 km of exclusive ways, a fleet of 392 buses, 74 tramways, 1545 sharing-bicycles and 22 park-and-rides. The private fleet is composed of about 383000 vehicles (BRAUP, 2013).

Population data was obtained from Institut national de la statistique et des études économiques (Insee, 2012). The *Observatoire Régional Énergie Changement Climatique Air* (Orecca, 2012) consolidated data on energy consumption of Aquitaine.

Cincinnati

Founded in 1788, the city of Cincinnati, at the Southwest tip of Ohio State, counts about 300 000 inhabitants, making it the third largest in Ohio. However, its metropolitan area comprises parts in the neighbor States of Kentucky and Indiana, and reaches over 2 million inhabitants. The city is home to some important companies in the United States and has a much-diversified economy. In this study, authors considered as Cincinnati the conurbation that comprises land in three American states: Ohio, Kentucky and Indiana (OKI).

The transit system has a fleet of 344 buses and 43 park-and-rides. Private fleet is composed of about 1397000 vehicles (BRAUP, 2013).

In the USA, population data for the 8 counties which compose Cincinnati Metropolitan area, known as OKI, in reference to the three states where the conurbation spreads (Ohio, Kentucky and Indiana), as well as population data of the three states were obtained from US Census (2010). Energy consumption information for the three states, in turn, were obtained from the US Energy Information Administration (EIA, 2011a).

Curitiba

The city of Curitiba, located in southern Brazil, is the capital of the State of Paraná. The city has the fourth GDP in the country. It was founded in 1693, but only in the XX and XXI centuries, it had its strongest growth. It is an important national junction way between the coast and the interior of Paraná.

The city has about 1.8 million inhabitants, and its metropolitan area over 3 million. With diversified economic activity, it has several industries, the automobile being the second pole of Brazil. The tertiary sector, likewise, is the largest employer. In this work authors considered as Curitiba the conurbation known as *Núcleo Urbano Central* (NUC) (Central Urban Core), composed by urban areas of 14 municipalities.

The transit system has a total extension of 81 km and a fleet of 1925 buses. Private fleet is composed of about 1760000 vehicles (BRAUP, 2013). Data on the population of Curitiba was obtained from *Instituto Brasileiro de Geografia e Estatística* (IBGE, 2010) and data on the fiscal added value for each municipality which compose the NUC was obtained from *Instituto Paranaense de Desenvolvimento Econômico e Social* (IPARDES, 2011). Energy data was obtained from COPEL (2013) – state level energy company –, the enterprise that annually (up to 2010) had been producing the Energy Outlook of Paraná State. As this research was based in Curitiba, authors could obtain from the coordinator of Paraná Energy Outlook 2011 data on energy consumption in the Metropolitan Area of Curitiba, a wider scale than NUC, despite results had not yet been published.

Figure 1 shows the urban area of each city, all in the same scale, highlighting the metropolitan areas considered in this work. It demonstrates the greater sprawling of OKI, and the high density of the Central Urban Core of Metropolitan Area of Curitiba (NUC), especially in relation to the total population. As a guideline of the *Ignis Mutat Res* Program, data was taken as much updated as possible. Accordingly, for OKI and NUC, 2011 data was considered, while for CUB, 2010 data.

Data colection

General features of the three cities considered were collected as shown in **Table 1**. Next, available data is presented in the actual form it was found for each city.

CUB

Data was collected from the most recent sources available at the time the research was conducted, thus, population data is from 2011, whilst energy data is from 2010. Population data from the Gironde is presented in **Table 2**. Energy data was obtained for the whole Aquitaine (Region where Gironde is located) from the *Bilan énergétique de la région Aquitaine*, 2010 (ORECCA, 2012), show on **Table 3**.

OKI

Population data comprises shares in three different states: Ohio, Kentucky and Indiana. Data source is the United States Census Bureau (US CENSUS, 2010) and energy data was obtained from the US Energy Information Administration (EIA, 2011a), respectively **Tables 4** to **6**.

NUC

Population and economic data were collected respectively from *Instituto Brasileiro de Geografia e Estatística* (IBGE, 2010) and from *Instituto Paranaense de Desenvolvimento Econômico e Social* (IPARDES), as showed in **Table 7**. Data on energy consumption of the municipalities of NUC was collected directly from the sources where they were produced, in a closer scale then usually published. **Table 8** shows electricity consumption.

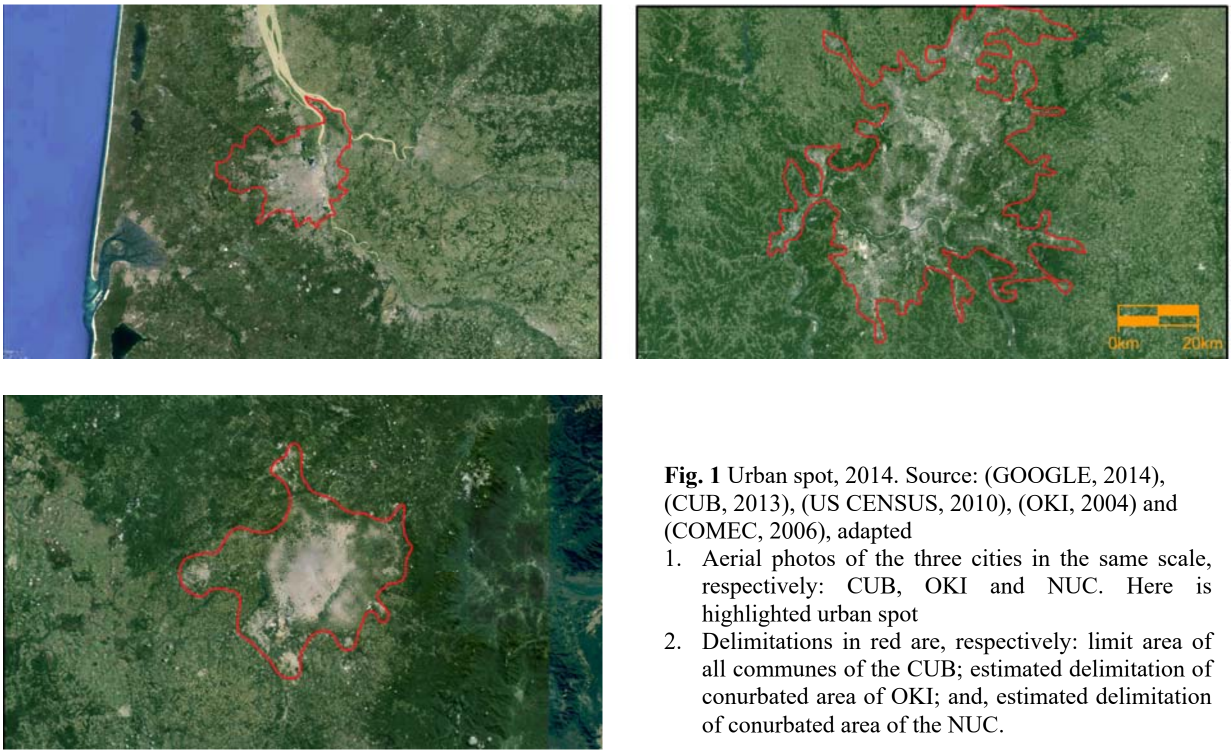

Fig. 1 Urban spot, 2014. Source: (GOOGLE, 2014), (CUB, 2013), (US CENSUS, 2010), (OKI, 2004) and (COMEC, 2006), adapted

1. Aerial photos of the three cities in the same scale, respectively: CUB, OKI and NUC. Here is highlighted urban spot
2. Delimitations in red are, respectively: limit area of all communes of the CUB; estimated delimitation of conurbated area of OKI; and, estimated delimitation of conurbated area of the NUC.

Table 1. General data on transportation in CUB, OKI and NUC

	Bordeaux (CUB)	Cincinnati	Curitiba (NUC)
Population	721 744	1 744 122	2 993 678
Surface (km²)	579	6713	1449
Population density (km²)	1247	260	2066
Per capita product (Euro)	26710	39673	15280
Displacements / day	3.67	7.44	4.94
Motorized and mechanized displacements/day	3.11	6.17	1.33
Average distance in motorized vehicles (km)	6.4	11.1	8.2
Average distance in public transportation (km)	6.7	12.7	9.4
Average duration of private motorized displacements (min)	16.1	13.3	25.4
Average duration of public transportation displacements (min)	34.7	20.5	50.9
Share using walking or bicycle (%)	28	6	30
Share using private, motorized modes (%)	59	93	23
Share using public transportation (%)	11	1	47
Average traffic speed (km/h)	26.6	50.2	25.5
Average public transportation speed (km/h)	12.5	37.2	23.0
Mortality rate by traffic accidents (deaths / 100,000 inh./year)	2.21	5.15	4.71
Exclusive public transportation lane length (km)	44	0	81
Exclusive public transportation line length (km/1000 inh.)	0.06	0	0.03
Exclusive public transportation lane length (km/urbanized area ha)	0.0017	0	0.0028
Bus fleet	392	344	1925
Hybrid bus fleet	30	27	60
Tram fleet	74		
Shared bicycles	1545		
Park and ride parking places	22	43	
Public transportation fleet / 1000 inh. (including shared bicycles)	2.786	0.197	0.643
Public transportation fleet / 1000 inh. (excluding shared bicycles)	0.646	0.197	0.643
Busses / 1000 inh.	0.543	0.197	0.643
Trams / 1000 inh.	0.108		
Km Trams / inh.	0.0609		
Park and ride / 1000 inh.	0.0305	0.0247	
Private cars / 1000 inh.	531	801	588
Average distance in private cars (km)	5.7	10.5	7.2
Average distance in cars as a passenger (km)	4.5	10.6	4.1
Average occupation rate of private cars	1.36	1.17	2.35
Public transportation budget	163.3 M E	$90M	R$ 74 M
Revenues (tickets)	55.8 M	$30 M	R$ 68 M
Costs of attracting and social solidarity policies (estimated)	30.6ME	No data	14.17 % of income
Trips / year	117 M	16.15 M	302.4 M
Ticket price	1.40 E	US$ 1.75	R$ 2.70

Source: BRAUP (2013)

Table 2. Population data of the *communes* of *Communauté Urbaine de Bordeaux* (CUB), 2011

Commune	Population
Ambarès et Lagrave	13270
Ambès	2894
Artigues-près-Bordeaux	7245
Bassens	6899
Bègles	24913
Blanquefort	14779
Bordeaux	239157
Bouliac	3106
Carbon-blanc	6885
Eysines	19571
Bruges	14903
Gradignan	23063
Cenon	22242
Floirac	16202
Le Bouscat	23095
Le Taillan-Médoc	9099
Martignas-sur-Jalle	7227
Parempuyre	7978
Saint-Aubin-de-Médoc	6186
Saint-Médard-en-Jalles	27719
Talence	40600
Le Haillan	8933
Lormont	19799
Mérignac	66142
Pessac	58025
Saint-Louis-de-Montferrand	2034
Saint-Vincent-de-Paul	1050
Villenave-d'Ornon	28420
Total	721436

Source: Adapted of INSEE (2012).

Table 3. Energy Consumption of Aquitaine, 2010 (ktoe)

	Coal	Petroleum products	Natural gas	Other non-renewable	Electricity	Renewable energy	Urban heating and steam	Total
Residential	0	756	667	0	781	443	12	2659
Tertiary	0	324	339	0	584	4	8	1260
Transportation	0	2457	0	0	16	164	0	2637
Industrial	37	140	360	5	444	563	207	1757
Agriculture	0	178	15	0	34	0	0	226
Total	37	3855	1381	5	1859	1174	227	8539

Source: Adapted of ORECCA (2012).

Table 4. OKI counties population (2010)

County	Population	Urb (2010)	Urban population
Butler, OH	368130	90,66%	333736
Clermont, OH	197363	77,28%	152529
Hamilton, OH	802374	97,77%	784466
Warren, OH	212693	82,73%	175969
Boone, KY	118811	86,73%	103042
Campbell, KY	90336	84,70%	76518
Kenton, KY	159720	93,02%	148578
Dearborn, IN	50047	46,94%	23493
Total			1798331

Source: US CENSUS (2010), adapted

Table 5. Energy consumption by carrier, 2011 (ktoe)

State	OH	KY	IN
Coal	30809	25467	33601
Natural gas	21309	5761	16007
Gasoline	14467	6315	8812
Distillate fuel oil	7588	4571	5685
Jet fuel	1908	1419	1290
Lpg	796	844	660
Heavy fuel oil	78	0	40
Other petroleum	4332	2371	2769
Nuclear energy	3926	0	0
Hidroelectricity	93	728	101
Biomass	2875	1285	2709
Other renewable	154	73	927
Net interstate flow of electricity	8142	-655	-282
Total	96477	48179	72320
Total	216975940		

Source: Adapted of EIA (2011a).

Table 6. Energy consumption by sector, 2011 (ktoe)

State	Residential	Commerce	Industrial	Transportation	Total
Ohio	23622	17930	30995	23904	96451
Kentucky	9621	6383	20268	11894	48166
Indiana	14029	9498	33112	15667	72305
TOTAL	216923				

Source: Adapted of EIA (2011a).

Table 7. Socio-economic data of NUC municipalities, 2011

Municipality	Estimate Population (2011)	Urbanization rate (2010)	Fiscal added value – TOTAL in Millions R$ (2011)	Primary fiscal added value in Millions R$ (2011)	Secondary fiscal added value in R$ (2011)	Tertiary fiscal added value in R$ (2011)	Average income in R$ (2010)
Almirante Tamandaré	104350	95.82%	481.8	3.0	328.5	150.2	1084.47
Araucária	121032	92.51%	15301.9	67.4	12557.0	2673.0	2101.72
Campina Grande do Sul	39092	82.44%	477.6	2.1	209.3	266.2	1239.41
Campo Largo	113882	83.80%	1469.8	21.5	1049.4	398.8	1206.02
Campo Magro	25184	78.68%	104.3	4.7	63.5	33.2	1455.82
Colombo	215242	95.42%	1625.1	26.4	799.8	796.7	1152.05
Curitiba	1764541	100.00%	36231.6	50.4	14974.0	21193.3	1976.23
Fazenda Rio Grande	83118	92.96%	409.2	6.6	258.4	144.0	1072.61
Itaperuçu	24236	82.54%	168.3	1.1	97.2	71.2	923.09
Pinhais	118334	100.00%	2634.4	7.4	1151.3	1474.7	1351.25
Piraquara	94518	49.07%	281.2	0.5	165.6	114.8	1079.27
Quatro Barras	20135	90.38%	588.2	1.7	486.1	100.5	1540.82
Rio Branco do Sul	30751	71.92%	887.0	9.9	749.2	127.5	1212.06
São José dos Pinhais	268808	89.66%	17199.0	75.7	13124.7	3992.6	1706.18

Source: IBGE (2010 and 2011) and IPARDES (2011), adapted

Table 8. Electricity consumption of NUC municipalities, 2011 (MWh/year)

Municipality	Residential	Industrial	Commercial	Rural	Government	Street lighting	Public services	Own	Total
Almirante Tamandaré	53079	44878	13333	3514	2030	4265	5152	19	126270
Araucária	73649	443528	55479	8623	6429	11828	2534	102	602172
Campina Grande do Sul	23204	34446	14451	3519	1388	2944	817	2	80771
Campo Largo	66344	141067	32361	6330	4212	11744	4751	100	266909
Campo Magro	12097	4498	2855	3623	826	1251	558	0	25708
Colombo	126430	122384	49754	7421	4648	10962	8327	99	330025
Curitiba	1567804	1097907	1367632	1157	146159	115142	108311	11260	4415372
Fazenda Rio Grande	45840	51612	14438	1864	2560	4455	1937	30	122736
Itaperuçu	8990	9963	2962	1149	327	1147	931	0	25469
Pinhais	87148	111145	46091	100	6816	12862	30967	102	295231
Piraquara	40887	15817	9857	2640	8642	3078	1835	8	82764
Quatro Barras	12632	62764	5518	1144	837	2806	1749	65	87515
Rio Branco do Sul	12251	11733	5023	2416	1322	2256	2317	9	37327
São José dos Pinhais	166848	595917	127825	17827	9102	16413	15785	193	949910

Source: Adapted of COPEL (2013).

Table 9. Consumption of petroleum fuels by NUC municipalities, 2011

2011	Diesel	Gasoline	Fuel oil	PLG	Ethanol	Natural gas	Electricty	Kerosene
Unit	L	L	kg	kg	L	m³	MWh	L
Conversion factor to TEP	8.48E-04	7.70E-04	9.59E-04	1.11E-03	5.34E-04	8.80E-04	8.60E-02	8.22E-04
Municipality								
Almirante Tamandaré	1.43E+07	6.16E+06	6.18E+05	2.87E+06	2.20E+06	1.77E+06	1.26E+05	0.00E+00
Araucária	5.49E+07	2.69E+07	2.03E+07	1.17E+07	8.83E+06	5.62E+07	6.02E+05	1.05E+06
Campina Grande do Sul	1.26E+08	1.42E+07	9.32E+04	1.46E+06	4.17E+06	1.76E+06	8.08E+04	0.00E+00
Campo Largo	5.13E+07	2.72E+07	1.94E+06	5.77E+06	7.93E+06	5.40E+06	2.67E+05	0.00E+00
Campo Magro	1.07E+06	1.21E+06	0.00E+00	2.90E+05	2.90E+05	3.84E+05	2.57E+04	0.00E+00
Colombo	1.39E+08	4.05E+07	2.89E+04	1.06E+07	1.09E+07	5.97E+06	3.30E+05	0.00E+00
Curitiba	4.35E+08	6.42E+08	1.17E+06	9.05E+07	1.99E+08	1.33E+08	4.42E+06	1.17E+06
Fazenda Rio Grande	3.36E+07	1.24E+07	0.00E+00	3.18E+06	3.74E+06	1.50E+06	1.23E+05	0.00E+00
Itaperuçu	2.43E+06	2.84E+06	4.07E+04	0.00E+00	8.30E+04	6.19E+05	2.55E+04	0.00E+00
Pinhais	1.93E+07	3.89E+07	0.00E+00	1.16E+07	1.26E+07	9.68E+06	2.95E+05	0.00E+00
Piraquara	4.62E+06	4.51E+06	0.00E+00	2.96E+06	1.40E+06	1.03E+06	8.28E+04	0.00E+00
Quatro Barras	1.69E+07	5.99E+06	6.05E+05	2.24E+06	2.00E+06	2.16E+06	8.75E+04	0.00E+00
Rio Branco do Sul	1.15E+07	3.67E+06	3.77E+05	2.47E+06	1.30E+06	3.26E+06	3.73E+04	0.00E+00
São José dos Pinhais	2.40E+08	8.11E+07	5.07E+05	2.15E+07	2.46E+07	6.32E+07	9.50E+05	1.42E+08

Source: ANP *apud* COPEL (2013) and COMPAGÁS *apud* SCHMID (2012), adapted.

Data on natural gas consumption were considered from COMPAGÁS (state level gas company) *apud* Schmid *et al.* (2012), that is, 133176090 m³ in 2010 to the municipality of Curitiba. Concerning petroleum fuels, data were obtained from ANP (National Agency of Petroleum, Natural Gas and Biofuel) *apud* COPEL, as shown in **Table 9**.

Up to the time this research was finished there was no consolidated data on energy consumption by sector for Paraná State (where Curitiba is located), so the percentage adopted was from Schmid *et al.* (2012), who considered 2010 data.

Energy conversion factors

When converting fuel amounts into electricity and back, each country adopts its own method, causing a possible construct failure in the present research. In Brazil and France, the net heat value is considered, particularly for petroleum products. In the United States, the gross heat value (thus, a higher value) is considered. This difference can be up to 10% in the case of petroleum fuels and up to 40% in the case of firewood (EIA, 2011b).

Furthermore, gross and net heat values may vary from year to year according to characteristics of each fuel produced. The World Energy Balances (IEA, 2013a) presents country data on fuels, with explanation of the average heat value of each fuel and its average heat values from year to year.

Regarding conversions, American energy outlooks are in BTU and the conversion factor of 1 million BTU = 0.0251995796 toe (IEA, 2013b and EIA, 2011b) was used. Regarding the equivalence of kWh to toe, in the case of conversion of electricity, the Énergétique Bilan de la région Aquitaine informs the relationship 1 toe = 11630 kWh = 42 GJ (ORECCA, 2012), or 1GWh = 85.845 toe, also following IEA (2013b).

In the US, energy outlooks of the states present consumption by primary energy source, i.e.: the original energy carrier (such as coal in the case of a coal thermoelectric power plant), and using the average heat value of coal that year as energy consumed in BTU per unit volume for the consolidation of consumption in a State. Although, in fact, that energy has been converted into electricity (secondary source) and then, consumed.

In the balance of Aquitaine (France), on the other hand, energy consumption is presented by secondary energy sources (those actually consumed), not showing in the matrixes whether primary sources of electricity are nuclear fuel, fossil fuel or hydroelectric power.

For NUC data, 2009 and 2011 (EPE, 2009, 2013a, 2013b) factors were used, this due to the fact that the 2009 Brazilian National Energy Balance (BEN – *Balanço Energético Nacional*) was the latest balance to present the average fuel densities in Brazil. In 2011, a conversion factor based on net volumetric heat value was adopted for fuels, for conversion to toe. Natural gas consumption for Curitiba was as obtained from COMPAGÁS (2009) *apud* Schmid *et al.* (2012).

In the case of sources of Bordeaux and Cincinnati, authors had neither access to the minimum or medium fuel density rates, nor to the net or gross heat value for each energy carrier. Therefore, it was necessary to choose matrixes already produced in toe, for Bordeaux, and in BTU for Cincinnati.

Such divergence of energy units and conversion factors became an important point of the present work. Despite of such possible error sources, energy consumption is presented in details, focusing on the most reliable energy source available.

RESULTS

Energy Matrixes

Once data collection was completed, energy matrixes of the three metropolitan areas were assembled. First, energy matrixes of the entire metropolitan areas considering all economy sectors and by energy carrier were compiled. Next, more detailed, partial energy matrixes representing only the transportation sector were assembled. **Tables 10** to **12** show results for CUB. Results for the OKI are shown in **Tables 13** to **15**. **Tables 16** to **18** show results for NUC.

Table 10. Energy Matrix of the CUB, by energy carrier, 2010 (toe)

Communes	Coal	Petroleum products	Natural gas	Other non-renweable fuels	Electricity	Renewable energy	Urban heating and steam	Total	
Ambarès et Lagrave	149.37	14844.48	5514.70	20.19	7367.74	4739.57	916.43	1.84%	33552.47
Ambès	32.58	3237.37	1202.68	4.40	1606.80	1033.63	199.86	0.40%	7317.32
Artigues-près-Bordeaux	81.55	8104.61	3010.85	11.02	4022.55	2587.66	500.34	1.00%	18318.59
Bassens	77.66	7717.56	2867.06	10.49	3830.45	2464.08	476.44	0.96%	17443.74
Bègles	280.43	27868.91	10353.26	37.90	13832.13	8898.04	1720.49	3.45%	62991.16
Blanquefort	166.36	16532.52	6141.81	22.48	8205.56	5278.54	1020.64	2.05%	37367.89
Bordeaux	2692.06	267532.79	99388.03	363.79	132784.16	85418.41	16516.17	33.15%	604695.41
Bouliac	34.96	3474.52	1290.78	4.72	1724.51	1109.35	214.50	0.43%	7853.35
Carbon-blanc	77.50	7701.90	2861.24	10.47	3822.67	2459.08	475.48	0.95%	17408.35
Eysines	220.30	21893.08	8133.25	29.77	10866.16	6990.07	1351.57	2.71%	49484.20
Bruges	167.76	16671.23	6193.34	22.67	8274.41	5322.82	1029.20	2.07%	37681.42
Gradignan	259.61	25799.41	9584.44	35.08	12804.98	8237.29	1592.73	3.20%	58313.54
Cenon	250.37	24881.00	9243.25	33.83	12349.15	7944.05	1536.03	3.08%	56237.68
Floirac	182.38	18124.35	6733.17	24.65	8995.63	5786.78	1118.91	2.25%	40965.87
Le Bouscat	259.97	25835.20	9597.74	35.13	12822.75	8248.72	1594.94	3.20%	58394.45
Le Taillan-Médoc	102.42	10178.59	3781.33	13.84	5051.92	3249.84	628.38	1.26%	23006.32
Martignas-sur-Jalle	81.35	8084.48	3003.37	10.99	4012.56	2581.23	499.10	1.00%	18273.07
Parempuyre	89.80	8924.58	3315.47	12.14	4429.53	2849.46	550.96	1.11%	20171.94
Saint-Aubin-de-Médoc	69.63	6919.96	2570.76	9.41	3434.58	2209.42	427.20	0.86%	15640.96
Saint-Médard-en-Jalles	312.02	31007.84	11519.37	42.16	15390.07	9900.25	1914.27	3.84%	70085.98
Talence	457.01	45417.16	16872.41	61.76	22541.83	14500.88	2803.83	5.63%	102654.88
Le Haillan	100.55	9992.89	3712.34	13.59	4959.76	3190.55	616.91	1.24%	22586.60
Lormont	222.87	22148.14	8228.00	30.12	10992.75	7071.50	1367.32	2.74%	50060.69
Mérignac	744.53	73989.70	27487.06	100.61	36723.20	23623.58	4567.76	9.17%	167236.44
Pessac	653.16	64909.62	24113.83	88.26	32216.50	20724.48	4007.20	8.04%	146713.04
Saint-Louis-de-Montferrand	22.90	2275.33	845.28	3.09	1129.31	726.47	140.47	0.28%	5142.86
Saint-Vincent-de-Paul	11.82	1174.58	436.36	1.60	582.98	375.02	72.51	0.15%	2654.87
Villenave-d'Ornon	319.91	31792.01	11810.68	43.23	15779.28	10150.62	1962.68	3.94%	71858.42
Total	0.45%	44.24%	16.44%	0.06%	21.96%	14.13%	2.73%		
	8120.82	807033.82	299811.86	1097.41	400553.91	257671.39	49822.32		824111,53

Table 11. Energy Matrix of the *Communauté Urbaine de Bordeaux*, by sector (CUB), 2010 (toe)

Communes	Petroleum products	Electricity	Renewable energy	Total	
Ambarès et Lagrave	9919.19	64.59	662.09	0.58%	10645.87
Ambès	2163.24	14.09	144.39	0.13%	2321.72
Artigues-près-Bordeaux	5415.57	35.27	361.48	0.32%	5812.31
Bassens	5156.93	33.58	344.22	0.30%	5534.73
Bègles	18622.22	121.27	1243.00	1.10%	19986.49
Blanquefort	11047.16	71.94	737.38	0.65%	11856.47
Bordeaux	178767.49	1164.14	11932.38	10.52%	191864.01
Bouliac	2321.70	15.12	154.97	0.14%	2491.79
Carbon-blanc	5146.47	33.51	343.52	0.30%	5523.50
Eysines	14629.13	95.26	976.47	0.86%	15700.86
Bruges	11139.85	72.54	743.56	0.66%	11955.95
Gradignan	17239.36	112.26	1150.69	1.01%	18502.32
Cenon	16625.68	108.27	1109.73	0.98%	17843.67
Floirac	12110.83	78.87	808.37	0.71%	12998.08
Le Bouscat	17263.28	112.42	1152.29	1.02%	18527.99
Le Taillan-Médoc	6801.41	44.29	453.98	0.40%	7299.68
Martignas-sur-Jalle	5402.11	35.18	360.58	0.32%	5797.87
Parempuyre	5963.48	38.83	398.05	0.35%	6400.36
Saint-Aubin-de-Médoc	4623.97	30.11	308.64	0.27%	4962.73
Saint-Médard-en-Jalles	20719.68	134.93	1383.00	1.22%	22237.60
Talence	30348.10	197.63	2025.68	1.79%	32571.40
Le Haillan	6677.33	43.48	445.70	0.39%	7166.51
Lormont	14799.56	96.37	987.84	0.87%	15883.77
Mérignac	49440.49	321.96	3300.06	2.91%	53062.51
Pessac	43373.11	282.45	2895.07	2.55%	46550.63
Saint-Louis-de-Montferrand	1520.39	9.90	101.48	0.09%	1631.78
Saint-Vincent-de-Paul	784.86	5.11	52.39	0.05%	842.36
Villenave-d'Ornon	21243.67	138.34	1417.97	1.25%	22799.98
Total	93.17%	0.61%	6.22%		
	539266.28	3511.71	35994.98		578772.96

Table 12. Partial energy matrix for transportation of the *Communauté Urbaine de Bordeaux*, by energetic, 2010 (toe)

Communes	Oil products	Electricity	Renewable energy	Total	
Ambarès et Lagrave	9919.19	64.59	662.09	0.58%	10645.87
Ambès	2163.24	14.09	144.39	0.13%	2321.72
Artigues-près-Bordeaux	5415.57	35.27	361.48	0.32%	5812.31
Bassens	5156.93	33.58	344.22	0.30%	5534.73
Bègles	18622.22	121.27	1243.00	1.10%	19986.49
Blanquefort	11047.16	71.94	737.38	0.65%	11856.47
Bordeaux	178767.49	1164.14	11932.38	10.52%	191864.01
Bouliac	2321.70	15.12	154.97	0.14%	2491.79
Carbon-blanc	5146.47	33.51	343.52	0.30%	5523.50
Eysines	14629.13	95.26	976.47	0.86%	15700.86
Bruges	11139.85	72.54	743.56	0.66%	11955.95
Gradignan	17239.36	112.26	1150.69	1.01%	18502.32
Cenon	16625.68	108.27	1109.73	0.98%	17843.67
Floirac	12110.83	78.87	808.37	0.71%	12998.08
Le Bouscat	17263.28	112.42	1152.29	1.02%	18527.99
Le Taillan-Médoc	6801.41	44.29	453.98	0.40%	7299.68
Martignas-sur-Jalle	5402.11	35.18	360.58	0.32%	5797.87
Parempuyre	5963.48	38.83	398.05	0.35%	6400.36
Saint-Aubin-de-Médoc	4623.97	30.11	308.64	0.27%	4962.73
Saint-Médard-en-Jalles	20719.68	134.93	1383.00	1.22%	22237.60
Talence	30348.10	197.63	2025.68	1.79%	32571.40
Le Haillan	6677.33	43.48	445.70	0.39%	7166.51
Lormont	14799.56	96.37	987.84	0.87%	15883.77
Mérignac	49440.49	321.96	3300.06	2.91%	53062.51
Pessac	43373.11	282.45	2895.07	2.55%	46550.63
Saint-Louis-de-Montferrand	1520.39	9.90	101.48	0.09%	1631.78
Saint-Vincent-de-Paul	784.86	5.11	52.39	0.05%	842.36
Villenave-d'Ornon	21243.67	138.34	1417.97	1.25%	22799.98
Total	93.17%	0.61%	6.22%		
	539266.28	3511.71	35994.98		578772.96

Table 13. Energy matrix of the Cincinnati Metropolitan Area (OKI), by energy carrier, 2011 (toe)

County	Coal	Natural gas	Gasoline	Distillated fuel oil	Jet fuel	Lpg	Residual fuel	Other petroleum	Nuclear electric power	Hidroelectric power	Biomass	Other renewable	Net intersate flow of electricity
Butler, OH	891264	616435	418514	219499	55185	23036	2260	125314	113577	2697	83178	4447	235537
Clermont, OH	407339	281732	191275	100319	25221	10528	1033	57273	51909	1233	38015	2032	107649
Hamilton, OH	2094969	1448966	983741	515946	129715	54148	5312	294557	266969	6340	195514	10453	553643
Warren, OH	469937	325028	220670	115735	29097	12146	1192	66074	59886	1422	43857	2345	124192
Boone, KY	604729	136791	149955	108547	33689	20046	0	56308	0	17293	30518	1735	-15558
Campbell, KY	449066	101580	111355	80606	25017	14886	0	41814	0	12842	22662	1289	-11553
Kenton, KY	871968	197241	216223	156516	48577	28905	0	81192	0	24936	44004	2502	-22433
Dearborn, IN	121748	57998	31930	20599	4675	2392	146	10035	0	365	9815	3360	-1023
TOTAL	*36.94%*	*19.78%*	*14.52%*	*8.23%*	*2.19%*	*1.04%*	*0.06%*	*4.58%*	*3.08%*	*0.42%*	*2.92%*	*0.18%*	*6.06%*
	5911020	3165770	2323664	1317767	351176	166087	9942	732565	492340	67128	467564	28163	970453

Table 14. Energy matrix of the Cincinnati Metropolitan Area (OKI), by sector, 2011 (toe)

County	Residential	Commerce	Industrial	Transportation	Total	
Butler, OH	683356	518677	896659	691521	17.44%	2790213
Clermont, OH	312318	237054	409804	316049	7.97%	1275225
Hamilton, OH	1606269	1219181	2107649	1625460	40.99%	6558559
Warren, OH	360313	273483	472781	364618	9.20%	1471196
Boone, KY	228464	151571	481282	282438	7.15%	1143754
Campbell, KY	169655	112555	357395	209736	5.31%	849341
Kenton, KY	329426	218553	693968	407252	10.31%	1649199
Dearborn, IN	50830	34413	119977	56765	1.64%	261986
TOTAL	23.38%	17.28%	34.62%	24.71%		
	3740630	2765487	5539515	3953840		15999472

Table 15. Partial Energy Matrix for transportation of the of the Cincinnati Metropolitan Area (OKI), by energetic, 2011 (toe)

County	Gasoline	Distillatedfuel oil	Jet fuel	Other renewable	Total	
Butler, OH	418513.70	208350.74	55184.61	4446.84	17.36%	686496
Clermont, OH	191275.37	95223.56	25221.29	2032.36	7.94%	313753
Hamilton, OH	983740.94	489740.60	129714.67	10452.57	40.81%	1613649
Warren, OH	220669.74	109857.11	29097.19	2344.69	9.15%	361969
Boone, KY	149955.45	103034.02	33689.11	1735.32	7.29%	288414
Campbell, KY	111355.48	76512.07	25017.21	1288.63	5.42%	214173
Kenton, KY	216223.30	148566.49	48576.90	2502.19	10.52%	415869
Dearborn, IN	31929.91	19552.54	4674.90	3360.08	1.51%	59517
Total	58.77%	31.64%	8.88%	0.71%		
	2323664	1250837	351176	28163		3953840

Table 16. Energy matrix of the *Núcleo Urbano Central* of Curitiba Metropolitan Area by energetic, 2011 (toe)

Municipality	Diesel	Gasoline	Fuel oil	Lpg	Ethanol	Natural gas	Electricity	Jet fuel		Total
Almirante Tamandaré	11648.77	4543.09	568.33	3050.02	1123.13	1493.36	10405.30	0.00	1.24%	32832.02
Araucária	43065.53	19196.29	18051.45	12038.00	4361.41	45788.44	47907.96	801.12	7.21%	191210.20
Campina Grande do Sul	88238.94	8995.26	73.69	1339.87	1837.08	1273.71	5726.53	0.00	4.06%	107485.09
Campo Largo	36470.65	17556.23	1561.26	5370.23	3550.77	3984.21	19235.60	0.00	3.31%	87728.95
Campo Magro	716.91	735.12	0.00	253.27	121.84	265.67	1739.53	0.00	0.14%	3832.34
Colombo	112324.01	29757.90	26.44	11219.30	5576.36	5015.82	27082.25	0.00	7.21%	191002.07
Curitiba	368702.16	494518.49	1121.04	100487.44	106323.99	117194.96	379721.99	958.93	59.20%	1569029.00
Fazenda Rio Grande	26455.06	8876.61	0.00	3285.40	1858.45	1230.31	9812.20	0.00	1.94%	51518.03
Itaperuçu	1703.30	1802.44	32.18	0.00	36.58	449.38	1807.90	0.00	0.22%	5831.80
Pinhais	16355.10	29956.27	0.00	12838.94	6706.36	8521.32	25389.87	0.00	3.76%	99767.86
Piraquara	1923.90	1704.24	0.00	1612.95	365.67	446.37	3492.66	0.00	0.36%	9545.78
Quatro Barras	7017.51	2264.20	284.93	1223.54	524.07	933.71	3693.15	0.00	0.60%	15941.11
Rio Branco do Sul	4803.41	1385.72	177.58	1346.29	339.33	1407.82	1575.21	0.00	0.42%	11035.37
São José dos Pinhais	99956.69	30651.81	238.75	11715.23	6447.51	27298.55	40086.39	57181.46	10.32%	273576.40
TOTAL	30.92%	24.60%	0.84%	6.26%	5.25%	8.12%	21.80%	2.22%		
	819381.95	651943.69	22135.66	165780.48	139172.56	215303.63	577676.54	58941.50		**2650336.02**

Table 17. Energy matrix of the *Núcleo Urbano Central* of Curitiba Metropolitan Area, by sector. 2011 (toe)

Municipality	Energy	Residential	Industrial	Commerce	Transportation	Public		Total
Almirante Tamandaré	50	12855	18552	7820	50817	2156	3.48%	92250
Araucária	56	14395	20774	8756	56905	2415	3.90%	103301
Campina Grande do Sul	16	4143	5979	2520	16379	695	1.12%	29733
Campo Largo	47	12269	17706	7463	48502	2058	3.32%	88047
Campo Magro	10	2548	3676	1550	10071	427	0.69%	18281
Colombo	102	26405	38106	16062	104383	4429	7.15%	189488
Curitiba	875	226861	327388	137997	896800	38053	61.43%	1627974
Fazenda Rio Grande	38	9934	14336	6043	39269	1666	2.69%	71286
Itaperuçu	10	2572	3712	1564	10167	431	0.70%	18456
Pinhais	59	15214	21955	9254	60141	2552	4.12%	109175
Piraquara	23	5963	8605	3627	23572	1000	1.61%	42790
Quatro Barras	9	2340	3376	1423	9249	392	0.63%	16790
Rio Branco do Sul	11	2843	4103	1730	11240	477	0.77%	20404
São José dos Pinhais	119	30986	44717	18849	122491	5198	8.39%	222360
Total	0.05%	13.94%	20.11%	8.48%	55.09%	2.34%		
	1424	369329	532987	224659	1459987	61950		2650336

Table 2. Partial Energy Matrix for transportation of the *Núcleo Urbano Central* of Curitiba Metropolitan Area, by energetic. 2011 (toe)

Municipality	Diesel	Gasoline	Ethanol	Natural gas	Jet fuel	Total	
Almirante Tamandaré	9877.62	4543.09	1123.13	141.27	0.00	1.00%	15685.11
Araucária	36517.56	19196.29	4361.41	4331.58	801.12	4.17%	65207.95
Campina Grande do Sul	74822.49	8995.26	1837.08	120.49	0.00	5.48%	85775.33
Campo Largo	30925.40	17556.23	3550.77	376.91	0.00	3.35%	52409.31
Campo Magro	607.91	735.12	121.84	25.13	0.00	0.10%	1490.01
Colombo	95245.51	29757.90	5576.36	474.50	0.00	8.37%	131054.26
Curitiba	312642.18	494518.49	106323.99	11086.62	958.93	59.13%	925530.21
Fazenda Rio Grande	22432.65	8876.61	1858.45	116.39	0.00	2.13%	33284.09
Itaperuçu	1444.32	1802.44	36.58	42.51	0.00	0.21%	3325.86
Pinhais	13868.36	29956.27	6706.36	806.11	0.00	3.28%	51337.11
Piraquara	1631.38	1704.24	365.67	42.23	0.00	0.24%	3743.52
Quatro Barras	5950.52	2264.20	524.07	88.33	0.00	0.56%	8827.11
Rio Branco do Sul	4073.06	1385.72	339.33	133.18	0.00	0.38%	5931.30
São José dos Pinhais	84758.60	30651.81	6447.51	2582.44	57181.46	11.60%	181621.82
Total	44.39%	41.65%	8.89%	1.30%	3.77%		
	694797.56	651943.69	139172.56	20367.68	58941.50		1565222.99

DISCUSSION

Shortcomings of the method

When building energy matrixes for urban areas using energy accounting inferences, several obstacles were identified, as summarized in **Table 19**. Next, those items are commented, in order to subsidize future work on the subject.

Table 3. Shortcomings in the elaboration of partial urban energy matrixes

	City	Energy
Concepts	Urban Urban limits	Heat power conversion to electricity. Urban energy carriers
Data	Urban population GDP or added value by sector on geographic reference	Energy consumed from primary sources in physical units. Energy consumed from secondary sources. Average annual heat power by oil product. Scale as close to metropolis as possible
Access	Official sources	Direct contact to officer in charge of energy outlooks
Delimitation	Urban population on geographic references	Site of energy carriers consumption or sales
Method	Presumption that one inhabitant consumes the same in urban and rural settings. Presumption that each unit of wealth generated demands the same amount of energy. Presumption that energy consumption will occur in the geographic delimitation	

Concepts

A precise definition of concepts is one of the problems because cities in different countries were considered. Uniformity in the definition of what is urban, based on physical, rather than political (official) criteria, is desirable for the refinement of results. A related and relevant question is on the limits of what is considered urban. An agreement on the concept of urban, based on solid criteria such as the maximum distance between buildings considered together with population density and further considerations – even including large areas without buildings, such as airports, enclaves, water bodies – such as it is done in the USA model (US CENSUS, 2010), would be of great value. A geographically referenced database, in effect, is the tool that would allow a precise definition of what is urban regardless of country.

In some countries, like Brazil and France, energy carriers obtained from oil are accounted for on the base of the net heat value, whereas in the USA the gross heat value is considered.

In some cases, for example, for nuclear power plants an efficiency of 33% is assumed when gross heat power is converted into electricity (IEA, 2012), what distorts comparisons among countries that use no such definition, as the US which measure its conversion from gross heat power subtracting the total energy content of electricity retail sales (EIA, 2011b).

There are energy carriers which are typical of urban areas; other are untypical. For example, in the case of Curitiba, biomass was not considered (although its use is observed, for example, firing pizza ovens and as a widely used heat source in industrial boilers). However, this fact leads to no apparent differences if one looks for a partial, transportation-related energy matrix.

Data

A preliminary definition of what is urban will allow the urban population to be more precisely accounted. In the same way, when considering data on the Gross Domestic Product or the Added Value to the Economy, data collection should be geographically referenced as much as possible, allowing a more accurate inference from wealth generated.

As official data is used, the scale of official energy data is a relevant factor. The area encompassed by energy balances should be as close as possible to the urban definition in order to preserve accuracy in the top-down approach. Scales much larger than the considered city may result in significant distortions.

Although classical, the definition of primary and final energy sources has to be commented. Final is the energy carrier as effectively offered for human purposes. Energy balances establish a relationship between primary and final energy values. However, such a relationship has an implicit geographical abstraction, as few primary energy sources (*e.g.* solar energy) are available within the city limits. A city balance of primary energy would show how related economic, social and environmental impacts of energy exploration and transformation are distributed outside the city limits. On the other hand, a city energy balance of final energy would be very useful to show how society uses energy and what impacts are associated to the final use – for example, air pollution.

Access to official data

In the present work, authors looked for data in the scale as close as possible to the city limits. Population data is easily obtained for urban limits. However, official energy data is frequently distributed only in larger scales, a fact which may cause a major construct error. In the case of Cincinnati, energy outlooks from three States of Ohio, Kentucky and Indiana had to be put together to yield a metropolitan matrix. What actually happens in the process of compilation statistics is that the larger scale results are based on a closer scale, which may remain as intermediate data. When dealing with data on Curitiba, authors had access to data in a closer scale, what allows a much more accurate estimative. That was possible because officers in charge of the energy outlooks provided the authors access to local data – not usually released. Authors had access to such data scale neither on OKI, nor on CUB.

Delimitation

Above, the difference was mentioned between the domain where primary energy is obtained and the domain where final energy is made available to consumers. A further difficulty in the analysis is that final energy may be in the form of storable energy carriers, which may be consumed somewhere else, possibly apart from the purchase site. That means that both the aggregated value by the final service (e.g. delivery of goods to the destination) and the environmental impacts of the final use of energy (such as noise and particulate matter pollution) take place somewhere else.

This generates another construct error in this method. A farmer can pack his truck and carry vegetables from the countryside to the city: most probably, the value of the products will be added to the farmer`s region, whereas the goods will be sold in the city markets or restaurants. What is urban population? The share that works within the city limits or that one who lives there? What area should be considered? The densely built area only, or also the sparsely built area, which is directly connected to the city economy? Same questions arise in the case of long trips by truck, train, ship or airplane.

Method

Finally, a potential construct error lies on the presumption that energy consumption will be the same for each inhabitant living in a rural or in an urban area, or that the energy consumed generates same wealth regardless of location. This is the basis of the technical-accounting inference, also its main fragility.

Ignis Mutat Res Final Report

Socioeconomic data on the three cities considered in this study is summarized in **Table 20**, from the final report by the American-Brazilian-French team to the Ignis Mutat Res Program (BRAUP, 2013). Per capita income was normalized according to the purchase power parity - PPP (World Bank, 2014).

The urban area of Cincinnati, with its relatively low population density, reflects the USA urban model, sprawled, what can be noticed from its urban spot, as shown in Fig. 1. At the other extreme, Curitiba is the densest city analyzed.

When considering GDP per capita based on PPP (purchase power parity) or on the international dollar, another difference becomes clear. The ratio between Bordeaux, Cincinnati and Curitiba is respectively of 1.80:1.70:1.00, respectively. The combination of the cities matrixes and Table 20 above, we achieve information on the energy consumption in the three cities (**Table 21**).

Table 20. Data of Bordeaux, Cincinnati and Curitiba metropolitan areas

		CUB (2010)	OKI (2011)	Cincinnati (conurb.)	RMC (2011)	NUC (2011)
area	km^2	578	6819	2971	16627	1358
population	Inhabitants	721436	2172191	1398692	3223836	2872667
density	Inhabitants/km^2	1248.16	318.55	470.78	193.89	2115.37
gdp per capita	Local currency	26710	US$ 29000		R$ 31188	
	PPP (2010 in the CUB, 2011 in OKI and NUC)	0.87	1		1.83	
	International dollar	30701.15	29000		17042.62	

Source: BRAUP (2013).

Table 21. Data of energy consumption of Bordeaux, Cincinnati and Curitiba metropolitan areas

	CUB (2010)	OKI (2011)	NUC (2011)
Total urban consumption (ktoe)	1824,11	16003.64	2650.34
Total consumption in urban transportation (ktoe)	578.77	3953.84	1565.22
Per capita urban consumption (toe/inhab./year)	2.53	11.44	0.92
Per capita transportation consumption (toe/inhab./year)	0.80	2.83	0.54
Environmental productivity (GDP in international dollar / toe/year)	12142.30	2534.55	18472.29

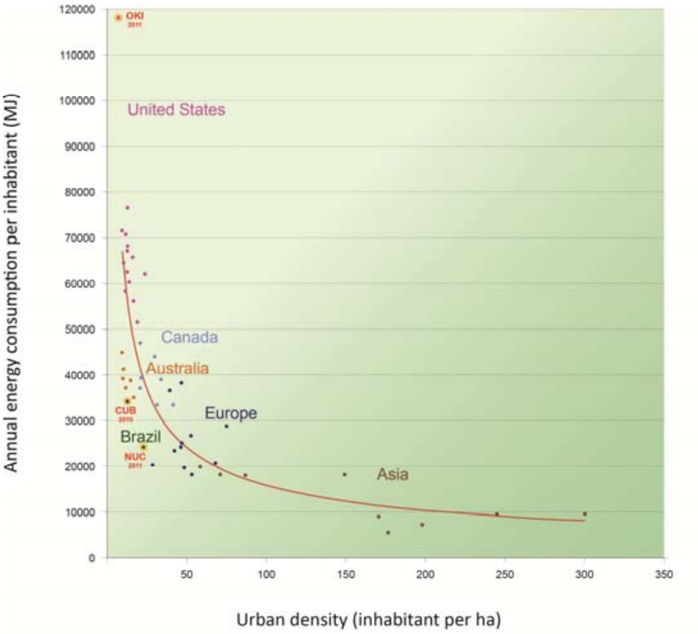

Fig. 1 Urban density and energy consumption per inhabitant due to transport of 46 world cities, 1999**.** Source: (KENWORTHY & LAUBE, 1996 *apud* LE NÉCHET, 2012) and authors, adapted

The highest absolute value of energy consumption was verified in Cincinnati, mainly because of its high industrial activity. The relation on energy consumption per capita in the cities was of 2.74:12.41:1.00, respectively for Bordeaux, Cincinnati and Curitiba. When considering the per capita energy consumption for mobility only, the ratio was of 1.47:5.19:1.00.

A first thought in the attempt to interpret such indicators is given by the population density data. Kenworthy and Laube (1996) presented a hyperbolic curve (**Fig. 1**), which reveals the continents clearly defined by characteristic ratios. Despite the 20-year gap between that publication and the indicators obtained in the current research, according to IEA (2013a), energy consumption per capita has had not a great increase in OECD countries during the period.

Curitiba has the lowest per capita income of the three cities. On the other hand, it is the city, which produces more wealth with the same amount of energy per capita. The relation for Bordeaux, Cincinnati and Curitiba was, respectively, of 0.66:0.14:1.00.

Approach to energy consumption in each city

Kenworthy and Laube (1996) stated that the use of car is directly linked to the infrastructure which is made available for them and to the average distance travelled, and that the amount of passengers transported is greater, the higher the population density.

It is noticeable that certain geographic domains present a high energy consumption for mobility, as it is the case of oil, in the State of California (GHANADAN & KOOMEY, 2005). Oil consumption for mobility is high, and so, in minor scale as it is here. Nevertheless, transportation may not correspond to the biggest share of energy consumption in highly industrialized regions as Cincinnati or in Taiwan (Yophy *et al.*, 2010).

A bottom-up approach to the construction of energy matrixes would yield a possibly more precise result. It is the case of some recently published research (SHABBIR & AHMAD, 2010; ZHOU *et al.*, 2013; PAES et al., 2013). However, authors indicated that their studies considered only the main roads. Such fine mobility data is simply not available.

In the larger study made by Le Néchet (2012), data on energy consumption was obtained from UITP, that collects data on transportation in cities worldwide, and that, through the project Millenium Cities Database for

Sustainable Transport, collects data on public transportation for its diffusion, which includes direct data survey, official and other statistics, and some estimates. It is mainly a bottom-up approach. For urban characteristics, Le Néchet (2012) adopted consolidated data from EEA. His conclusions coincide with some of the current work. For example, Cincinnati, the city with highest motorization rate (BRAUP, 2013) has the biggest energy consumption per capita among the three cities. Cincinnati is also the most sprawled city, as shown in the aerial photos, what suggests highest energy consumption on transportation.

CONCLUSIONS

Transportation energy matrixes for three conurbation areas of Bordeaux (CUB), Cincinnati (OKI) and Curitiba (NUC) were presented. Results confirm expectations based on known factors like population density or income. Authors consider, however, methodological observations to be more relevant.

Energy consumption on transportation in cities is a complex issue where some variables involved are interdependent, and the context cannot be always quantified. An interpolation from a bigger to a smaller scale was practical. Nevertheless, it probably would be more accurate to use wealth indicators with a spatial link.

Moreover, in the delimitation of an area, the choice of a physical criterion as the conurbation (the visible city unit) is more likely to be representative. A smaller delimitation, as of parts of a city, or a city as officially defined would make no meaning in this purpose, as a transportation energy matrix in the urban scale occurs over the borders of a county, or even state. Besides, as it is hard to collect data on energy consumption for metropolitan areas, a smaller scale would be even harder. Bigger scales would not make it possible to distinguish what is urban.

Finally, we present a diagram (**Fig. 2**) that shows how both top-down and bottom-up approaches to the energy consumption for transportation in cities are related. Indeed, a bottom-up approach is preferable, for it would yield results that are more trustworthy. However, a top-down approach reveals other issues, as energy consumption in a city as a whole, exposing more clearly the energy context not only in the transportation sector, but also in other sectors as well. Therefore, it should not be discarded.

For building a transportation energy matrix in an urban scale, the ideal method would be an origin-destination survey with an energetic bias, with geographically referenced information.

This work aimed to bring light to a complex issue with a feasible method. Energy matrixes of cities may become a useful tool to guide public policies in favor of better usage of resources and even to strengthen the environmental concern in the cultural dimension.

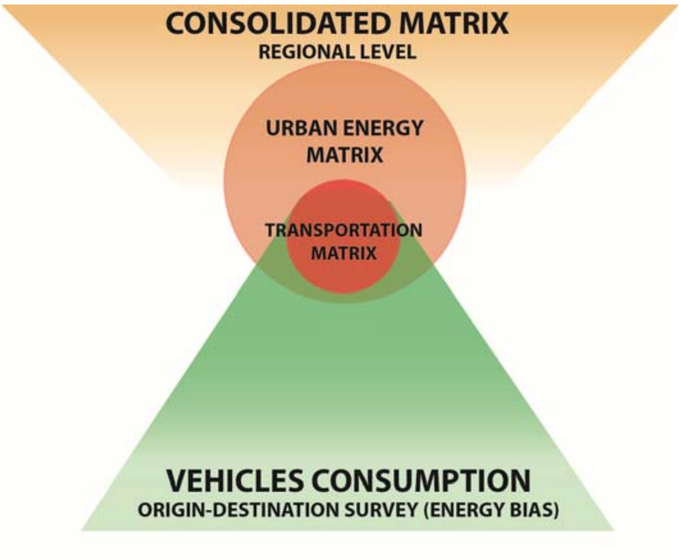

Fig. 2 Comparative diagram between top-down and bottom-up approaches about urban energy matrixes

Acknowledgements

We thank the French Government for the support to the project within the Ignis Mutat Res Program, COPEL (*Companhia Paranaense de Energia*) for providing data closer to Curitiba Metropolitan Area, and Eng. José Mário Moraes Silva from Lactec, in Curitiba, for precious comments. We thank the interest and collaboration of the research fellows: Cristina de Araújo Lima (Brazilian leader) and Márcia de Andrade Pereira from UFPR, Curitiba; Rebecca Williamson, Frank Russel and Carla Chifos from the University of Cincinnati, and Juan Kent Fitzsimmons (Team leader), Guy Tapie and Patrick Godier from the *École Nationale Supérieure d'Architecture et de Paysage de Bordeaux*.

REFERENCES

BRAUP. (2013). *Ignis Mutat Res. Penser l'architecture, la ville et les paysages au prisme de l'énergie*. Bordeaux: Fitzsimons, J. K.; Godier, P.; Tapie, G.; Gerbeaud, F.; Leroy, J.; Cincinnati: Williamson, R.; Chifos, C.; Ozaki, A. G.; Parent, O.; Russell, F.; Curitiba: Lima, C. A.; Pereira, M. A.; Schmid, A. L.; Silva, J. M. M. , Bureau de la Recherche Architecturale Urbaine et Paysagère. Métropoles et mobilités durables à l'épreuve d'un nouveau paradigme énergétique.

Cameron, I., Kenworhty, J., Lyons, T. (2003). Understanding and predicting private motorised urban mobility. Transportation Research Part D, pp. 267–283. doi:10.1016/S1361-9209(03)00003-8

COMEC. (2006). Coordenação da Região Metropolitana de Curitiba. *Plano de desenvolvimento integrado da Região Metropolitana de Curitiba*. Curitiba.

COPEL. (2013). Companhia Paranaense de Energia. Interview to Paraná Energetic Outlook Coordinator, Mrs. Rosicler do Rocio Brustolin. Curitiba. April 2013.

CUB. (2013). Communauté urbaine de Bordeaux. Source: 28 communes de La Cub. Accesses in April 2013. Available at http://www.lacub.fr/vie-democratique/28-communes-de-la-cub

EIA. (2011a). United States Energy Information Administration. Source: State Profile and Energy Estimates 2011. Accessed in July 2013. Available at http://www.eia.gov/state/

EIA. (2011b). United States Energy Information Administration. Source: Annual Energy Review 2011. Accessed in April 2013. Available at http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf

EPE. (2009). Empresa de Pesquisa Energética. *Balanço Energético Nacional 2009 – Ano base 2008: Resultados.* Rio de Janeiro.

EPE. (2013a). Empresa de Pesquisa Energética. *Balanço Energético Nacional. Séries completas.* Ministério de Minas e Energia. Balanço Energético Nacional. Accessed in July 2013. Available at https://ben.epe.gov.br/BENSeriesCompletas.aspx

EPE. (2013b). Empresa de Pesquisa Energética. *Balanço Energético Nacional 2013 – Ano Base 2012: Relatório síntese.* Rio de Janeiro.

Ghanadan, R., Koomey, J. G. (2005). Using energy scenarios to explore alternative energy pathways in California. Energy Policy, pp. 33:1117–1142. doi:10.1016/j.enpol.2003.11.011

GOOGLE. (2014). Google Earth. Satelites photos. Accessed in July 2013.

IBGE. (2010). IBGE CIDADES@. Available at Instituto brasileiro de geografia e estatística. Accessed in April 2012. Available at: www.ibge.gov.br/cidadesat/painel/painel.php?codmun= 410690

IBGE. (2011). *Instituto Brasileiro de Geografia e Estatística.* Source: Estimativas preliminares para 1º de julho de 2011. Accessed in July 2013. Available at http://www.ibge.gov.br/home/estatistica/populacao/estimativa2011/estimativa.shtm

IEA. (2012). Electricity information 2012. International Energy Agency, Paris. Accessed in December 2013. Available at http://www.iea.org/media/training/presentations/statisticsmarch/electricityinformation.pdf

IEA. (2013a). International Energy Agency. World Energy Balances. Documentation for beyond 2020 files. IEA. Accessed in December 2013. Available at http://www.iea.org/media/statistics/Documentation_WORLDBAL.pdf

IEA. (2013b). International Energy Agency. Unit Converter. Accessed in March 2013. Available at http://www.iea.org/stats/unit.asp

INSEE. (2012). *Institut National de la Statistique et des Études Économiques*. Source: Cartes interactives. Accessed in July 2013. Available at: http://www.insee.fr/fr/bases-de-donnees/?page=statistiques-locales.htm

IPARDES. (2011). *Instituto Paranaense de Desenvolvimento Econômico e Social.* Source: *Perfil dos Municípios.* Accessed in July 2013. Available at: http://www.ipardes.gov.br/index.php?pg_conteudo=1&cod_conteudo =29

Kenworthy, J., Laube, F. (1996). Automobile dependence in cities: an international comparison of urban transport and land use patterns with implications for sustainability. Environmental Impact Assessment Review, pp. 16:279-308. doi:10.1016/S0195-9255(96)00023-6

Kuhnimhof, T., Buehler, R., Wirtz, M., Kalinowska, D. (2012). Travel trends among young adults in Germany: increasing multimodality and declining car use for men. Journal of Transport Geography, pp. 443–450. doi:10.1016/j.jtrangeo.2012.04.018

Le Néchet, F. (2012). Urban spatial structure, daily mobility and energy consumption: a study of 34 European cities. Cybergeo: European Journal of Geography. Article 580. Available at http://cybergeo.revues.org/24966. doi:10.4000/cybergeo.24966

ORECCA. (2012). *Bilan énergétique de la région Aquitaine. Année 2010. L´Observatoire Régional Energie Changement Climatique Air d´Aquitaine.* Accessed in December 2013. Available at http://www.orecca.fr/uploads/media/OR12ET01_-_Bilan_energetique_2010v2012_01.pdf

OKI. (2004). Ohio Kentucky Indiana - Regional Council of Governments. Accessed in August 2013. Source: http://www.oki.org/.

PAES, N. C., PREVEDELLO, A. A., & TAVARES, S. F. (2013). *Consumo energético no movimento pendular: um estudo de caso entre Curitiba e Araucária. Encontro Latino Americano de Edificações e Comunidades Sustentáveis - ELECS*. Curitiba.

Shabbir, R., Ahmad, S. S. (2010). Monitoring urban transport air pollution and energy demand in Rawalpindi and Islamabad using leap model. Energy, An International Journal. Volume 35, Issue 5, pp. 2323-2332. doi:10.1016/j.energy.2010.02.025

Schmid, A. L., Tavares, S. F., Errera, M. R., Paes, N. C., Lima, C. A. (2012). *Modelagem do consumo de energia na cidade de Curitiba. Encontro Nacional de Tecnologia do Ambiente Construído - ENTAC*. Juiz de Fora.

UITP. (2006). *Union Internationale des Transports Publics* - Mobility in cities database. Bruxelas.

US Census. (2010). United States Census Bureau. Source: US Census 2010. Accessed in December 2013. Available at http://www.census.gov/2010census/

World Bank. (2012). World Bank. Accessed in july 2013, available at http://data.worldbank.org

WORLD BANK. (2014). GNI *per capita*, PPP (current international $). Accessed in January 2014. Available at http://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD/countries

Yin, R. (1994). Case Study Research: Design and Methods. Newbury Park, California Sage.

Yophy, H., Jeffrey, B. Y., Chieh-Yuc, P. (2010). The long-term forecast of Taiwan's energy supply and demand: LEAP model application. Energy Policy. Volume 39, Issue 11, pp. 6790-6803. doi:10.1016/j.enpol.2010.10.023

Zhou, J., Lin, J., Cui, S., Qiu, Q., Zhao, Q. (2013). Exploring the relationship between urban transportation energy consumption and transition of settlement morphology: A case study on Xiamen Island, China. Habitat international, pp. 70-79. doi:10.1016/j.habitatint.2011.12.008