Journal of Environmental Assessment Policy and Management
Vol. 21, No. 1 (March 2019) 1950002 (28 pages)

DOI: 10.1142/S1464333219500029

Energy–Economy–Environment Interactions: A Comparative Analysis of Lisbon and Sao Paulo Metropolitan Areas

Luís Cruz[*,**], Denise Imori[†,††], João-Pedro Ferreira[‡,§,‡‡],
Joaquim J. M. Guilhoto[¶,‖,§§], Eduardo Barata[*,¶¶] and Pedro Ramos[*,‖‖]

[*]*CeBER and Faculty of Economics, University of Coimbra, Coimbra, Portugal*
[†]*Sao Paulo State Department of Logistics and Transport, Brazil*
[‡]*Faculty of Economics, University of Coimbra, Coimbra, Portugal*
[§]*Research Unit on Governance, Competitiveness and Public Policies (GOVCOPP), Aveiro, Portugal*
[¶]*Organisation for Economic Co-Operation and Development (OECD), France*
[‖]*NEREUS, University of São Paulo Brazil and Regional Economics Applications Laboratory University of Illinois, USA*
[**]*lmgcruz@fe.uc.pt*
[††]*denise.imori@gmail.com*
[‡‡]*joao.pr.ferreira@gmail.com*
[§§]*joaquim.guilhoto@oecd.org*
[¶¶]*ebarata@fe.uc.pt*
[‖‖]*pnramos@fe.uc.pt*

Received 2 October 2017
Revised 26 July 2018
Accepted 26 November 2018
Published 13 February 2019

Metropolitan areas constitute a critical arena in which to protect the environment and handle climate change efforts, both because they are at the root of the problem and they form a suitable working ground to deal with their systemic nature. Using a multi-regional input-output modelling framework, with energy-environmental extensions, this paper proposes a comparative analysis of the Sao Paulo and Lisbon metropolitan areas, distinguishing territorial, production-based and consumption-based responsibilities. This research reveals that the consideration of interregional interactions and leakages to other regions/countries, as well as the appraisal of trade-offs between socio-economic and

[**]Corresponding author.

environmental targets, are critical for climate change policy's definition and monitoring. The results also stress the importance of tailoring policy measures to the territories and, concurrently, the need for significant changes regarding the discussion of climate change policies on a subnational scale, namely concerning policy concertation and coordination at the global, national and subnational levels.

Keywords: Environmental satellite accounts; environmental responsibility; input–output analysis; interregional trade; metropolitan regions; sustainability.

Introduction

Cities are systems of major demographic, economic and environmental complexity. Cities and metropolitan areas contain more than 50% of the world's population, generate more than 80% of global GDP, consume between 60% and 80% of the world's energy and account for more than 70% of human-induced global greenhouse gas (GHG) emissions (UN-Habitat, 2016). This is why these areas are both at the root of the problem and key drivers for climate change policy and action (Wei and Tang, 2014).

Climate change impacts do not have administrative borders, and thus it is widely accepted that political action on climate change requires (coordinated) responses at all levels (local and national as well as international) of government (Gonzalez *et al.*, 2011; Rootes *et al.*, 2012). Actually, human-induced climate change is a global externality of production activities (Stern, 2008), and its assessment must consider the connections between economies as trade links for production and consumption in different regions and countries (Ramrattan and Szenberg, 2007). Metropolitan areas are consumption centres for products and services that are produced locally or have their origins in other regions and/or other countries. Likewise, the production that occurs in these areas not only fulfils its own demand but also the demand in other regions of their respective countries and from other parts of the world. Ignoring these connections might result in a misleading analysis of the underlying driving forces of emission trends and lead to suboptimal mitigation policies (Peters *et al.*, 2011).

Hoekstra and Wiedmann (2014) point out that the Kyoto Protocol is an example of a well-intended, but ineffective, policy. The Kyoto Protocol adopts a fragmented, two-tier mitigation strategy; it sets reduction targets for Annex B countries with respect to GHG emissions within the territory, while the developing countries do not have emission commitments. In this setting, concerns about carbon leakage (i.e. increasing CO_2 emissions in countries outside of the agreement's control) arise. Peters *et al.* (2011) found that global CO_2 emissions grew by 39% from 1990 to 2008. Indeed, while emissions in developed countries have stabilised, emissions in developing countries have doubled. In the same period, the net emission transfers from non-Annex B to Annex B countries have grown by 17% per year on average. While it is not clear whether these increasing flows are caused by climate policy itself (i.e. whether they represent strong or weak "carbon leakage"), given the world economy dynamics, the increasing flows are enough to cause substantial concern for the effectiveness of climate regimes with limited participation (Peters and Hertwich, 2008).

Climate change assessment and sustainability promotion requires systemic approaches that are able to capture the multisectoral and inter-regional complex interactions between the economic, social and environmental dimensions (Gibson, 2006; Morrison-Saunders and Therivel, 2006; Almeida *et al.*, 2017).

Input-Output (IO) tables, either at the country or regional levels, allow for systematising and characterising the intra- and inter-sectoral relations of an economy, as well as of the corresponding trade flows (Miller and Blair, 2009). The well-established multi-regional input-output modelling framework allows for incorporating interregional trade flows, representing the linkages between industries and households located in different regions (Baynes *et al.*, 2011; Choi, 2015; Ferreira *et al.*, 2018). This is particularly important for metropolitan regions, with intensive trade flows and interregional income distribution (Ferreira *et al.*, 2017), as it allows for detailed allocation of the impacts associated with regional structural specificities and the identification of the regional spillover effects (Hewings *et al.*, 2001).

Furthermore, the construction of environmental satellite accounts, which consistently represent the existing links/feedbacks, allows for the extension of the analysis with respect to the use of primary fossil fuels by the economic system and greenhouse gas (GHG) emissions derived from their combustion (Machado *et al.*, 2001; Cruz and Dias, 2016; Pablo-Romero *et al.*, 2017). Environmentally extended IO models have been receiving considerable attention in evaluating energy and emissions embodied in trade (Baynes *et al.*, 2011; Peters and Hertwich, 2008; Andrew *et al.*, 2009), fully demonstrating their potential for the integrated analysis of the interactions between the economic, social and environmental pillars of sustainability (Hayami and Nakamura, 2007; Llop, 2007; Tunc *et al.*, 2007; Su *et al.*, 2010).

This paper explores the potential of a multi-regional input-output (MRIO) modelling framework, with energy-environmental extensions, for the comparative analysis of the different productive structures and regional interdependencies using as case studies the Sao Paulo and Lisbon metropolitan areas. The analysis is mainly focused on the identification of the intersectoral linkages and on how different industries/economic activities can assume different responsibilities in the use of fossil fuel energy resources and corresponding GHG emissions. Such a comprehensive assessment is a crucial step towards the definition, coordination and critical evaluation of climate change policies at the regional/subnational level. Accordingly, it will be possible to identify, e.g. the extent to which the Sao Paulo and/or Lisbon metropolitan areas may be tempted to reduce their GHG emissions "artificially", through some kind of carbon leakage within the country (or internationally).

Research Approach

This section is divided into three parts. First, we present a brief characterisation of the metropolitan areas of Lisbon and São Paulo, with reference to the rationale for their selection for the accomplishment of this study as well as the lessons that this choice potentiates, including an outline of the current climate policies in Brazil and Portugal, in which we underline the prevailing minimal focus on the distribution of the mitigation efforts by regions. Then, we describe the methodology and data sources used to account for energy–economy–environment interactions and regional environmental responsibility, detailing the construction of regional and environmental satellite accounts for the Sao Paulo and Lisbon metropolitan areas.

Case studies: Sao Paulo and Lisbon

Rationale for using Sao Paulo and Lisbon as case studies

Sao Paulo and Lisbon are the most populated metropolitan areas of Brazil and Portugal, respectively, as well as the most important economic centres of these countries (IBGE, 2014; INE, 2012b). Although, on a global scale, Brazil is considered a large country and Portugal a small one, both have in common the particularity of being economies with major regional asymmetries (at the geographic, economic, social and energy/environment levels). This context means that economic studies and policy recommendations should ideally be based on models that explicitly consider the interrelationships between different regions and their specificities, something that is empirically underexplored in the literature. Accordingly, and taking good advantage of the similarity between the MRIO models developed for Sao Paulo-Brazil and Lisbon-Portugal, this study considers a consistent accounting framework to develop a comparative analysis of these metropolitan areas' responsibility (following territorial, consumption and production-based principles) for energy use and CO_2 emissions.

Characterisation of the case studies

— *Socioeconomic characterisation*

Table 1. Socioeconomic characterisation of the metropolitan regions.

			Sao Paulo	Lisbon
Population (2015)		Total	20 443 152	2 821 876
		% of the country	10%	27%
Employment (FTE) (2009/2010)		Total	11 655 433	1 454 210
		% of the country	12%	30%
GVA (2009/2010)		Total	540 437 (10^6 R$)	53 284 (10^6 €)
		% of the country	19%	38%
Environmental Indicators (2010/2009)	Primary consumption of oil and derivatives (10^3 toe)	Total	12 757	2 946
		% of the country	16%	31%
	Primary consumption of natural gas (10^3 toe)	Total	3 307	755
		% of the country	17%	17%
	Primary consumption of coal (10^3 toe)	Total	970	16
		% of the country	8%	1%
	CO_2 emissions (10^3 tonnes)	Total	45 500	10 777
		% of the country	12%	24%
Unemployment rate (%) (December 2015)		in the region	13.9	12.5
		in the country	6.9	12.2

Source: IBGE (2018), INE (2018) and own calculation for the environmental indicators.

The metropolitan areas considered in this study are the major productive and consumption centres of their respective countries. But, as shown in Table 1, their size, either in absolute or relative terms, is quite different in terms of population, employment and Gross Value Added (GVA). Actually, the relative weight of the Lisbon metropolitan area on the country total is, at least, double for these three variables when compared with the relative weight of Sao Paulo in Brazil. A similar rationality applies for total CO_2 emissions. Regarding the primary energy consumption of fossil fuels, Sao Paulo has an higher relative burden for coal, a smaller one for oil and derivatives, and an equivalent share for natural gas, in comparison with Lisbon.[1] Furthermore, the unemployment rate is comparable in the Lisbon and Sao Paulo metropolitan areas, though in the case of Sao Paulo it is more problematic, as it is double the unemployment rate for Brazil.

Several economic, industrial and technological factors may affect the differences between these two regions. One potential source of differentiation is the sectoral specialisation of a region.

[1] This is associated with the allocation of fuel consumption (and oil derivatives) directly to the households that are located in Lisbon and use their cars to travel within the region.

Table 2. Sectorial specialisation — Location Quotient: Sao Paulo *versus* Lisbon.

6 sectors with the highest Location Quotient (sector's GVA in the region/sector's GVA in the country)			
Sao Paulo	LQ	Lisbon	LQ
Manufacture of pharmaceuticals	4.2	Air transport activities	2.2
Manuf. of paints, varnishes and similar coatings	2.9	Manufacture of pharmaceuticals	2.0
Passenger land transport activities	2.7	Manufacture of motor vehicles	1.8
Manufacture of motor vehicles	2.7	Information services activities	1.8
Manuf. of medical, precision and optical instruments	2.5	Financial intermediation and insurance serv. activit.	1.7
Financial intermediation and insurance serv. activit.	2.5	Other business services activities	1.5

Source: Own calculation (based on the SIIP-BR and MULTI2C models).

Table 2 shows that manufacturing is dominant in the Sao Paulo region. The region of Sao Paulo concentrates medium/high technology industries and highly qualified services. On the other hand, in the Lisbon metropolitan area, there is greater concentration on services (although there are some common sectors within the six).

— *Sector's energy intensity by region*

On the one hand, from Table 3.1, one can notice that, for the same industries, Sao Paulo is less energy intensive than the rest of Brazil. Besides having relatively

Table 3.1. Sectoral energy intensity — Brazil (1/2).

Six sectors with the highest Energy Intensity (sector's energy consumption/sector's output)			
Sao Paulo	(toe/10^6 R$)	Rest of Brazil	(toe/10^6 R$)
Passenger land transport activities	453.5	Passenger land transport activities	921.6
Manuf. of cement	276.5	Freight land transport activities	313.0
Freight land transport activities	226.9	Manuf. of cement	261.2
Manuf. of basic metals	64.7	Manuf. of basic metals	145.5
Manuf. of other non-metallic mineral products	47.9	Manuf. of fabricated metal products	67.5
Air transport activities	44.7	Manuf. of other non-metallic mineral products	47.4

Source: Own calculation (based on the SIIP-BR model).

Table 3.2. Sectoral energy intensity — Portugal (2/2).

6 sectors with the highest Energy Intensity (sector's energy consumption/sector's output)			
Lisbon	(toe/10^6 €)	Rest of Portugal	(toe/10^6 €)
Freight land transport	366.8	Prod. and distrib. of electricity, gas, steam and…	393.9
Manuf. of cement	263.1	Freight land transport	337.9
Mining and quarrying	194.9	Manuf. of cement	253.1
Manuf. of pharmaceuticals	145.9	Mining and quarrying	166.1
Passenger land transport	85.2	Manuf. of pharmaceuticals	151.0
Manuf. of other non-metallic mineral products	76.8	Manuf. of coke and refined petroleum products	85.2

Source: Own calculation (based on the MULTI2C model).

low energy intensity, Sao Paulo has a relative advantage in that it produces more of its energy from renewable sources. Actually, according to official energy balances, hydroelectricity and biomass energy represent 50% of the final energy use in Sao Paulo (against 40% in Brazil).

On the other hand, from Table 3.2 it is possible to confirm that, for the same activity sectors, there is greater energy intensity in the metropolitan area of Lisbon than in the Rest of Portugal. Nevertheless, with the exception of the pharmaceutical industry, these activity sectors are relatively unimportant (in terms of total output) in the Lisbon region. Furthermore, Lisbon has a disadvantageous relative position in terms of electricity generation, as only a small share of its energy is being provided by renewables.

— *Subnational climate change policies approach*

In what concerns to the current climate policies, the Brazilian position was formalised by the National Climate Change Policy (PNMC, in Portuguese — Law n° 12 187, dated December 29, 2009), which provides a legal framework for national actions aimed at mitigation and adaptation. The PNMC defines the country's national voluntary reduction targets for GHG emissions, advancing the policy from merely programmatic (Lucon and Goldemberg, 2010) to a legal commitment with clear environmental objectives that should guide subsequent policymaking. In Portugal, in 2015, within the framework of a "green growth strategy", the Portuguese Government approved the Strategic Framework for Climate Policy (QEPiC, in Portuguese, Resolution of the Council of Ministers no. 56/2015, dated 30 July 2015), which establishes the vision and objectives of the national climate policy by 2030, reinforcing its commitment to the development of a competitive, resilient and low carbon economy. The QEPiC considers both the National Program for Climate Change 2020/2030 (PNAC 2020/2030, in Portuguese) and the second phase of the National Strategy for Climate Change (ENAAC 2020, in Portuguese), which implement national policy guidelines for mitigation and adaptation to climate change, in conjunction with participation in the European Union Emissions Trading System.

Both Brazil and Portugal, have ratified and are committed to the Paris Agreement. But, in these two countries, as in the majority of other nations around the world, minimal focus is placed on the distribution of the corresponding mitigation efforts by regions. We argue that this might be particularly problematic in countries where there are considerable regional socio-economic disparities, as is the case for Portugal (see Cruz *et al.*, 2017), but it can be even more questionable in large countries, like Brazil, which has substantial regional differences in terms of economic development, physical geography, production systems and energy consumption (see Azzoni, 2013).

It is relevant to note that Brazil's 1988 Constitution divides the responsibilities for environmental policies and legislation between the three levels of government (Puppim de Oliveira, 2009), and several Brazilian states have established public policies on climate change.[2] There have also been advancements in municipal climate change policies, namely in the two most populous cities, Sao Paulo and Rio de Janeiro, which have established mandatory targets. However, the subnational policy elaboration processes, which have emerged autonomously, are detached from one another. The incongruities between the targets and the lack of convergence in actions increases the difficulty and reduces the effectiveness of the mitigation measures and the respective monitoring (Romeiro and Parente, 2011; Forum Clima, 2012). Thus, although the subnational policies indicate advances towards a less intensive effect on climate change, the regulatory aspects still require improvement.

On the other hand, European Union Member-States' national adaptation strategies seem to have some influence on local planning agendas. However, these strategies are non-binding policies and neither involve specific local policies or provide clear guidelines for local level adaptation (Campos *et al.*, 2017). Additionally, in Portugal, the local level of governance is typically challenged with problems of limited resources and a small scale in regard to developing and implementing climate change adaptation and mitigation policies. Clearly, these difficulties can be minimised by introducing some forms of coordination and

[2] Four Brazilian states have mandatory targets for reducing GHG emissions: Sao Paulo and Rio de Janeiro in the most developed Southeast regions; Mato Grosso do Sul in the Central-West region, and Paraíba in the Northeast region.

complementarity between municipalities, namely among those belonging to the same metropolitan area or region, as well as by reinforcing medium-levels of governance (between local and national authorities). Actually, the strengthening of the role of regional government institutions, as might be the case for the Regional Coordination and Development Commissions and/or of the Intermunicipal Communities, giving them additional responsibilities for the definition and implementation of environmental and climate strategies and policies, will be critical for the desirable engagement and coordination among the three levels of government.

Finally, it is important to stress that this criticism is not exclusive to Brazil and Portugal, as it also applies to other countries where subnational climate policies have emerged. Literature concerning these problems has flourished in recent years, and subnational governments have led climate change efforts in many countries, for example the USA (Lutsey and Sperling, 2008; Schreurs, 2008). Although there are advantages associated with the engagement of subnational governments in climate change policies — such as greater flexibility in implementing new policies (Puppim de Oliveira, 2009) and efficiency gains from the exploitation of local heterogeneities (Somanathan *et al.*, 2014) — most of the literature agrees that the possibility of coordination and complementarity problems exists and questions institutional capacity to take action on such policies.

In summary, as argued in UN-Habitat (2016), the measures envisaged at the global and national levels to fight climate change have yet to be accompanied by concerted measures at the city and local levels, and institutional, technical, economic and political changes are needed.

Methodology: The extension of the MRIO modelling framework to account for energy–economy–environment interactions and regional environmental responsibility

The MRIO-based modelling framework allows for the integration of the socio-economic dimension with the energy requirements and related CO_2 emissions, considering the links between sectors and regions of an economy. Adapting the approach used (for a national economy) by Cruz and Barata (2011, pp. 66–70) to an MRIO framework, here we take a step forward and apply it to estimate regional sectoral primary energy intensities per unit of total output (in terms of tons of oil equivalent (toe)/million EUR). This research is focused on energy requirements and CO_2 emissions generated from fossil fuel consumption, so three types of primary energy are considered: coal, natural gas, and oil or oil refined products.

Furthermore, using an MRIO framework, the energy requirements and corresponding CO_2 emissions can be "attributed" to the final demand for goods and services, accounting for the direct as well as the indirect emissions (Miller and Blair, 2009). Depending on the components considered, it is possible to distinguish the energy flows and CO_2 emissions associated with regional domestic demand from those associated with external demand, divided between interregional (Rest of Brazil/Rest of Portugal) and international (Rest of the World) exports. It is also possible to estimate the energy flows and CO_2 emissions "embodied" in the region's (interregional and international) imports.

Estimating the energy and CO_2 emissions embodied in export-related goods and services is relatively straightforward, as (no matter where they are going to be consumed) they were produced in the metropolitan area and, thus, the technology and coefficients are the ones applied to the estimations related to domestic flows. Regarding an accurate calculation of the energy requirements and CO_2 emissions associated with imports, the task is not as straightforward as it is with exports, as new energy intensity coefficients should be estimated based on the IO tables of the relevant regions/countries from which the imports come. This is done for the imports from the Rest of the Country (for which we have the required IO data), but it would be a hugely demanding task for imports from foreign countries. However, as Machado *et al.* (2001) remark, if the aim is to assess the energy "saved" by a region/country, by importing non-primary energy goods, then the appropriate energy intensity coefficients to be used in assessing the energy embodied in imports is the same as that estimated for domestic industrial production.[3] Choi (2015) also subscribes to this approach, applying the domestic technology assumption to foreign imported products.

Likewise, it is possible to estimate the employment embodied in a given structure of regional production and consumption and therefore somehow extend the assessment to the social dimension.

This means that one may attribute those impacts to the ultimate source of its demand, attaching responsibilities to producers and/or consumers (Machado *et al.*, 2001; Wiedmann, 2009; Dietzenbacher *et al.*, 2012). Actually, as Choi (2015) remarks, regional environmental responsibilities associated with emissions attributable to regional production activities and/or to regional consumption can be classified according to distinct typologies. We follow a similar typology to the one proposed by Choi (2015), but extend it here by also considering the energy requirements embodied in a metropolitan area region's flows, as well as differentiating the energy requirements and CO_2 emissions flows embodied in trade with the other region that exhausts the country and with the rest of the world.

[3] See Cruz and Barata (2011, p. 69) for a detailed description of how to estimate the energy and CO_2 emissions embodied in imports.

Table 4. Typology of metropolitan region's (socio)environmental responsibility.

		DEMAND/Consumption *with origin in the :*			
		Metropolitan Area *(Sao Paulo / Lisbon)*	Rest of the Country *(Rest of Brazil/Portugal)*	Rest of the World *(other countries)*	*Total*
SUPPLY/Production *with origin in the:*	**Metropolitan Area** *(Sao Paulo / Lisbon)*	***Territorial Responsibility:*** Regional production activities that meet regional demand	Interregional Exports	International Exports	***Production-based responsibility***
	Rest of the Country *(Rest of Brazil/Portugal)*	Interregional Imports			
	Rest of the World *(other countries)*	International Imports			
	Total	***Consumption-based responsibility***			

Accordingly, our analysis focuses on three types of regional environmental (energy requirements and corresponding CO_2) responsibility (see Choi, 2015, p. 136):

- *Territorial responsibility:* the region is responsible for the energy use or CO_2 emissions from regional production activities that specifically meet regional demand.[4]
- *Production-based responsibility:* the energy needs and CO_2 emissions generated by the productive activities developed in a given region, regardless of the geographic origin of demand.[5]
- *Consumption-based responsibility:* the energy requirements and CO_2 emissions originating from all regional consumption demands regardless of the geographic region of origin (i.e. embodied in the goods and services consumed in the region, whether domestically produced or imported).

Table 4 schematically depicts this typology of (socio) environmental responsibility.

Actually, production processes have increasingly become sliced up into ever smaller (or fragmented) parts (Timmer *et al.*, 2014). This has led to an upsurge in trade in intermediate products, which corresponds to Baldwin's (2006) "second

[4] The concept of territorial responsibility used here is not equivalent to conventional territorial approaches that consider only direct energy requirements or direct CO_2 emissions from local sources. Actually, through the use of the MRIO approach, here we are considering direct plus indirect requirements/emissions, and the indirect ones (of upstream supply chains) may occur either inside or outside the region.

[5] An approach similar to the one followed by Choi (2015) is used in this analysis for full consideration of embodied energy requirements and corresponding CO_2 emissions associated with trade products, namely by estimating the indirect requirements/emissions of upstream supply chains.

wave of global unbundling", where the location of intermediate input production differs from the location of the final product production, and thus affects where GHG emissions actually take place. Interregional fragmentation also plays a role when focusing on regions. Very importantly, by means of global and domestic (interregional) value chains, consumption in any part of the world has environmental impacts in many other locations (Lenzen *et al.*, 2004; Muñoz and Steininger, 2010; Wiebe *et al.*, 2012). Therefore, taking into account the cases of the Sao Paulo and Lisbon metropolitan areas, this work aims to evaluate how responsible the production and/or consumption of a region is, in terms of its emissions.[6]

Data

The MRIO framework(s)

The proposed interregional framework for Brazil is based on the SIIP-BR — "Intermunicipal Input-Output Model for the Brazilian Economy" — an interregional IO model developed for 134 sectors, 187 products, and the 5,565 Brazilian municipalities of 2009. The SIIP-BR is the result of a long-term research project conducted and coordinated by Prof. Joaquim Guilhoto at the University of São Paulo Regional and Urban Economics Lab (NEREUS).

The process of estimating the SIIP-BR can be summarised in the following steps: (a) by applying the methodology presented in Guilhoto and Sesso Fillho (2005 and 2010) it is possible to estimate the input–output matrices for the Brazilian economy based on the Brazilian System of National Accounts released by the Brazilian Statistical Office (IBGE); (b) based on information derived from the IBGE databases as well as from other sources the next step is done by expanding the number of sectors and products on the estimated national input–output matrices; (c) from the expanded national system, and by applying the methodology presented in Guilhoto *et al.* (2017) the interstate I-O system for the 27 states of Brazil (including the Federal District) is estimated; and (d) subsequently, based on the interstate IO system, each state is broken down into small regions

[6] For the case of Brazil, previous studies that analyse sectoral energy requirements and/or GHG emissions at the subnational level have been developed by applying either single-region (e.g., Carvalho *et al.*, 2013) or interregional IO models (e.g., Hilgemberg and Guilhoto, 2006; Carvalho and Perobelli, 2009; Imori *et al.*, 2018). For Portugal, environmental extended IO models have been developed and applied almost exclusively at the national level (Cruz and Barata, 2011; Ferreira *et al.*, 2014). Ferreira *et al.* (2018), with a tri-regional application, is a noticeable exception.

corresponding to their respective municipalities, which is done by a process of extraction, tabulation and processing of municipal information.[7]

The proposed MRIO framework to account for the Lisbon metropolitan area case is based on MULTI2C, a multi-sectoral and multi-regional framework developed by a group of researchers from the University of Coimbra (Portugal). This framework allows for the adoption of different geographic configurations and empirical applications (Ramos *et al.*, 2015). This particular application relies on the 2010 version of MULTI2C. The MULTI2C framework uses top-down non-survey methods to regionalise I/O tables (for the 30 Portuguese NUTS III regions), using detailed information provided by the Portuguese National and Regional Accounts, together with other detailed statistical information at the regional level from Statistics Portugal (INE) (population census, household expenditure survey, agricultural census and national forestry survey). The MULTI2C "Supply and Use Table" disaggregation specifies 431 products and 134 industries. The Portuguese Ministry of Employment and Social Security database was used as the main source for the determination of each industry's primary products supply, by region.

The interregional trade was also estimated according to the MULTI2C approach. As net interregional trade, by products, is determined by the commodity-balance method (Miller and Blair, 2009, p. 356),[8] the basic idea to estimate gross exports and imports consists of differentiating the levels of "regional tradability" (Ramos *et al.*, 2015). This means that the partition of each national input or other use, between regional imports and locally produced products, depends on a typology of tradability.

It is relevant to note that the Supply and Use format of both SIIP-BR and MULTI2C is not transformed into a symmetric one, when the Input-Output model is implemented, preserving its rectangular type framework (Miller and Blair, 2009, Chapter 5; Sargento *et al.*, 2011). Actually, this framework admits more products than industries producing them (134 sectors for both cases, 187 and 431 products for Sao Paulo-Brazil and Lisbon-Portugal, respectively). Preserving the richness of the high level of product disaggregation (minimising the information loss from official statistics, as this dichotomy products-industries is also adopted by modern National Accounts systems) is critical, as such products may have very different interregional and international trade coefficients (Cruz *et al.*, 2017).

[7] Different methodologies can be used in this process and an overview can be found in Ichihara *et al.* (2013).

[8] Miller and Blair (2009, pp. 347–361) provide a survey of the ways in which the literature deals with this issue of interregional trade estimation.

The environmental satellite account(s)

Regarding the regional environmental satellite accounts, it is relevant to note that generally, the data required for the estimation of (primary) energy consumption is not directly available in the appropriate, or consistent, form. Accordingly, there is a need to make assumptions and estimations in order to correlate the different data sources, with the final aim of obtaining suitable estimations of the physical quantities of the primary fuels used by each sector.

Regarding the Brazilian dataset, adopting a bottom-up approach, we considered data on the fossil fuel use by industry, at the state level.[9] First, we depart from the Brazilian Energy Balance (EPE, 2009) and reconcile the data from state energy balances. Official energy balances are available for 2008 for the states of: Alagoas, Bahia, Goiás, Minas Gerais, Rio de Janeiro, Sao Paulo, Paraná and Rio Grande do Sul. For Ceará and Espírito Santo, participation in the national energy use and the sectors' fuel structure from the 2007 and 2010 energy balances are considered, respectively.[10]

Following Montoya *et al.* (2014), we reconcile the data on fossil fuel use (in toe) from the energy balances with the industry classification of Brazil's Interregional IO Tables. Next, we estimate the corresponding CO_2 emissions by adopting the carbon emission factors and oxidation fractions from the Brazilian Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases (MCTI, 2010). In this study, we assume that the energy and CO_2 coefficients, at the industry level, for the metropolitan region of Sao Paulo, are the same as for the State of Sao Paulo.[11] Different from the Portuguese case, in the Brazilian approach the CO_2 emissions from households' direct use of fossil fuels (approximately 9% of the national emissions) are disregarded. Instead, the analysis is focused exclusively on the emissions generated by the various economic industries in their productive activities. This difference in terms of the decomposition of total energy use between (intermediate consumption by) producers and (direct final use of fuels by) final consumers, which is driven by information unavailability, does not significantly impact on the overall level of energy use and emissions generation, though

[9] The following fuels were considered: natural gas, steam coal, metallurgical coal, diesel oil, fuel oil, gasoline, LPG, kerosene, gas coke, coal coke, other oil by-products, and coal tar. The data also include fuels that are used in thermal power plants and the use of coke in iron and steel mills.

[10] Alagoas (2012), Bahia (2009), Ceará (2008), Espírito Santo (2013), Goiás (2009), Minas Gerais (2011), Paraná (2011), Rio de Janeiro (2013), Rio Grande do Sul (2010) and Sao Paulo (2009).

[11] This assumption regarding the regionalisation of energy and CO_2 coefficients is limited. However, subnational (city and metropolitan-level) industry-specific statistics are extremely scarce. Therefore, in the absence of detailed survey data, regionalisation methods typically have to be modelled or inferred using statistical data from wider spatial units (Kronenberg, 2009; Baynes *et al.*, 2011).

it should be taken into account when considering the responsibilities' allocation and discussion.

For the Portuguese case, we start by briefly presenting the estimation of primary fuel consumption (in physical terms) by each of the 134 sectors/431 products considered in the IO tables made available in INE (2012a), taking advantage of the 2010 "Energy Balance" statistics (DGEG, 2013). The values for the total consumption of coal, (crude) oil and natural gas (expressed in tonnes of oil equivalent (toe)), from the 2010 "Energy Balance" (DGEG, 2013), were considered as credible totals of Portuguese domestic energy use (by type of fuel) and it was from these that we derived the sectoral use of these three primary energy sources.[12] For all of the fuels, the figures for Exports and Change in Stocks were also directly found using data published in the 2010 "Energy Balance" (DGEG, 2013). Furthermore, the figures on primary fuel use by the other final demand components (i.e. for Final Consumption) were calculated using the corresponding purchase information (in monetary terms) available in the IO table; i.e. the physical figures for fuel use by final consumers were estimated applying the corresponding (monetary) proportions of the consumption by each household type to the physical figures for total energy use. Then, as a rule, the procedures to estimate the regional consumption of the primary fuels (in physical terms) were developed considering the structure of intermediate consumption for each sector that consumes each of the primary fuels in each of the NUTS III regions (INE, 2012b). The corresponding CO_2 emissions were then estimated using the conversion units for each type of fuel (for the Portuguese case) suggested by the Intergovernmental Panel on Climate Change (IPCC, 2006).

Results and Discussion

This section, on a basis of a comparative analysis of the two-case study metropolitan areas, presents (in Tables 5.1 and 5.2) and discusses the main results on the appraisal of the different types of (socio) environmental responsibility by region, according to the classification presented in Table 4.

[12] Moreover, it is important to note that in the "Energy Balance", the supply of each of the primary fuels to the Portuguese economy is calculated by adding together the figures for domestic production (in 2010 with zero values for all the fuels) and imports, and subtracting the figures for exports, international bunkers (in 2010 with zero values for all the fuels), and stock changes. As a result, this approach considers the total primary fuel used in the Portuguese economy, whether it is domestically produced or imported, and whether the fuel is used by the industrial production sectors or by final consumers.

Table 5.1. (Socio) Environmental responsibilities — *Sao Paulo metropolitan area* (1/2).

SUPPLY/Production *with origin in the:* / **DEMAND**/Consumption *with origin in the:*

	Sao Paulo metropolitan area	%	%	*Rest of Brazil*	%	*Rest of the World*	%	*Total*
Sao Paulo metropolitan area	Territorial responsibility	%	%	Interregional Exports	%	International Exports	%	***Production responsibility***
1 Oil and derivatives (10^3 toe)	**3,414**	30.4	32.8	5,673	50.6	2,131	19.0	**11,218**
2 Natural Gas (10^3 toe)	**983**	32.7	33.2	1,559	51.9	463	15.4	**3,005**
3 Coal (10^3 toe)	**224**	25.8	12.5	434	50.0	210	24.2	**868**
1+2+3=*Tt. fossil fuels (10^3 toe)*	**4,621**	30.6	30.5	7,666	50.8	2,804	18.6	**15,091**
4 CO_2 emissions (10^3 tonnes)	**12,104**	29.4	27.0	21,088	51.3	7,945	19.3	**41,137**
5 Employment (10^3 FTE)	**5,899**	50.6	51.7	4,569	39.2	1,188	10.2	**11,656**
Rest of Brazil	Interregional Imports					***Interregional***		
1 Oil and derivatives (10^3 toe)	4,847	46.6				826		
2 Natural Gas (10^3 toe)	1,307	44.1				252		
3 Coal (10^3 toe)	1,046	58.5				–612		
1+2+3=*Tt. fossil fuels (10^3 toe)*	7,200	47.5				466		
4 CO_2 emissions (10^3 tonnes)	22,788	50.9				–1,700		
5 Employment (10^3 FTE)	4,381	38.4				188		
Rest of the World	International Imports					***International***		
1 Oil and derivatives (10^3 toe)	2,134	20.5				–3		
2 Natural Gas (10^3 toe)	674	22.7				–211		
3 Coal (10^3 toe)	519	29.0				–309		
1+2+3=*Tt. fossil fuels (10^3 toe)*	3,327	22.0				–523		
4 CO_2 emissions (10^3 tonnes)	9,868	22.0				–1,923		
5 Employment (10^3 FTE)	1,114	10.0				47		
Total	***Consumption Responsibility***					***Total***		
1 Oil and derivatives (10^3 toe)	**10,395**					823		
2 Natural Gas (10^3 toe)	**2,964**					41		
3 Coal (10^3 toe)	**1,789**					–921		
1+2+3=*T. fossil fuels (10^3 toe)*	**15,148**					–57		
4 CO_2 emissions (10^3 tonnes)	**44,760**					–3,623		
5 Employment (10^3 FTE)	**11,421**					235		

Sao Paulo embodied trade balance (*embodied in exports – embodied in imports*)

Table 5.1 shows that the territorial responsibility of the Sao Paulo metropolitan area, in terms of the primary energy requirements for the local production of the goods and services demanded by the region's inhabitants, corresponds to $4,621 \times 10^3$ toe of fossil fuels (more specifically, $3,414 \times 10^3$ toe of oil, 983×10^3 toe of natural gas and 224×10^3 toe of coal). Furthermore, according to the estimation made through the model, the production of CO_2 emissions embodied in the domestic consumption by Sao Paulo's inhabitants was $12,104 \times 10^3$ tonnes in 2009. But, as the Sao Paulo economy also has relevant linkages with neighbouring regions and abroad, one can also observe from Table 5.1 that both the production-based and the consumption-based responsibilities of the Sao Paulo metropolitan area are noticeably higher than the territorial responsibility.[13]

Regarding the production-based responsibility, it was estimated that in 2009 there were $7,666 \times 10^3$ toe of fossil fuels embodied in Sao Paulo exports to the Rest of Brazil and $2,804 \times 10^3$ toe in its international exports. In other words, it is possible to say that from all of the primary energy needs for the production that occurs in Sao Paulo, 50.8% corresponds to the satisfaction of the final demand of the inhabitants of the Rest of Brazil and 18.6% corresponds to worldwide consumers. Accordingly, from the $41,137 \times 10^3$ tonnes of CO_2 emissions that are embodied in Sao Paulo's production, only 29.4% correspond to the satisfaction of Sao Paulo consumers' needs. This result is in line with the findings of Andrew and Forgie (2008) for New Zealand, where exports account for almost two-thirds of the emissions embodied in its production.

The use of disaggregated information with regard to the three types of fossil fuel sources discloses the distinct role of each fuel in each type of final demand. Indeed, the production that occurs to satisfy the demand from the Rest of the World (international exports) shows a larger dependence from coal (7.4%) than the one to satisfy local demand (4.8%). Otherwise, the consumption of Sao Paulo's inhabitants has a share of 11.8% of the coal embodied in the sum of all fossil fuels required, while the coal share in terms of Sao Paulo's production is only 5.7%.

In respect of the consumption-based responsibility, it is relevant to highlight that to satisfy the demand of Sao Paulo's consumers, only 27% of the CO_2 emissions are embodied in the production that occurs in the region, as 50.9% and 22% correspond to goods and services imported from the Rest of Brazil and internationally (from the Rest of the World), respectively.

Furthermore, it can be said that, in 2009, the amount of primary energy embodied in Sao Paulo's international exports ($2,804 \times 10^3$ toe) (i.e. in production that occurred in Sao Paulo, but was sold to other countries) was smaller than the

[13] The results in Table 5.1, presented at the aggregated level, were obtained from a disaggregated sectorial level, though such sectorial decomposition is now shown for parsimonious reasons. Relating the energy requirements at the sectoral level and comparing with those concerning energy intensity (in Table 3.1), one can notice that the sectors that are more highly energy intensive are not necessarily the ones whose total production requires more energy. This is explained by the "scale effect" of the final demand (corresponding to the fact that total energy requirements of any sector are given by the product of the intensity per unit of final demand and the level of final demand). Similar reasoning applies to the sectorial decomposition of CO_2 emissions.

amount of primary energy that was "saved" by Sao Paulo because it internationally imported the corresponding goods and services (produced in other countries) instead of producing them in Sao Paulo ($3,327 \times 10^3$ toe) to satisfy the demand of the residents of Sao Paulo. Accordingly, in 2009, Sao Paulo faced a negative embodied primary energy trade balance (-523×10^3 toe). On the other hand, the estimation of the "primary energy trade balance" with regard to the Rest of Brazil reveals the opposite conclusion, with the natural gas and oil and derivatives embodied in interregional exports to the other regions of Brazil being smaller than the contents embodied in their imports from the rest of the country. Overall, taking into account interregional and international trade altogether, Sao Paulo is estimated to have more natural gas (41×10^3 toe) and oil and derivatives (823×10^3 toe) embodied in its exports than in its imports, and the contrary happens with coal (-921×10^3 toe). Thus, the total energy requirements are slightly higher (57×10^3 toe) for the consumption-based than the production-based responsibility.

Correspondingly, the Sao Paulo metropolitan area presents less embodied CO_2 emissions in its production than its consumption-based responsibility. In fact, it can be said that in 2009 the Sao Paulo economy produced a smaller volume of GHG emissions ($41,137 \times 10^3$ tonnes) in satisfying others' consumption than were associated with the consumption of its inhabitants ($44,760 \times 10^3$ tonnes).

The analysis of the trade flows also allows for identifying and quantifying interesting consequences in terms of the employment embodied in production and consumption. For example, the production that occurs in the Sao Paulo metropolitan area incorporates almost the same number of jobs to satisfy the final demand of non-residents ($4,569 + 1,188 = 5,757 \times 10^3$ FTE) as to satisfy its own inhabitants ($5,899 \times 10^3$ FTE). Regarding the consumption-based responsibility for employment, the difference becomes more significant, as to satisfy the final demand of Sao Paulo's inhabitants the number of jobs required in the Sao Paulo metropolitan region ($5,899 \times 10^3$ FTE) is higher than outside of the region ($5,522 \times 10^3$ FTE, namely $4,381 \times 10^3$ FTE in the Rest of Brazil and $1,114 \times 10^3$ FTE in the Rest of the World).

In terms of the Lisbon metropolitan area, it was estimated that, in 2010, $633 + 546 = 1,179 \times 10^3$ toe of oil and derivatives, $822 + 765 = 1,587 \times 10^3$ toe of natural gas and $452 + 140 = 592 \times 10^3$ toe of coal were embodied in the Lisbon (interregional and international) imports. In other words, these figures correspond to the amounts of the fuels that would have been embodied in Lisbon's production if those non-primary energy goods and services to satisfy Lisbon residents' final demand had not been imported (from the Rest of the Country and from the Rest of the World) but instead were produced in Lisbon. Furthermore, these figures are

Table 5.2. (Socio) Environmental responsibilities — *Lisbon metropolitan area* (2/2).

DEMAND/Consumption *with origin in the:*

SUPPLY/Production *with origin in the:*	***Lisbon metropolitan area***		***Rest of Portugal***		***Rest of the World***		***Total***	*Lisbon embodied trade balance (embodied in exports − embodied in imports)*
Lisbon metropolitan area	Territorial responsibility	% / %	Interregional Exports	%	International Exports	%	***Production responsibility***	
1 Oil and derivatives (10^3 toe)	**1,826**	62.0 / 60.8	460	15.6	660	22.4	**2,946**	
2 Natural Gas (10^3 toe)	**386**	51.1 / 19.6	186	24.6	183	24.2	**755**	
3 Coal (10^3 toe)	**2**	12.5 / 0.03	4	25.0	10	62.5	**16**	
1+2+3=*Tt. fossil fuels (10^3 toe)*	**2,214**	59.6 / 39.7	650	17.5	853	22.9	**3,717**	
4 CO_2 emissions (10^3 tonnes)	**6,460**	59.9 / 40.0	1,846	17.1	2,471	22.9	**10,777**	
5 Employment (10^3 FTE)	**1,024**	69.8 / 62.6	238	16.2	206	14.0	**1,468**	
Rest of Portugal	Interregional Imports							***Interregional***
1 Oil and derivatives (10^3 toe)	633	21.1						–173
2 Natural Gas (10^3 toe)	822	41.7						–636
3 Coal (10^3 toe)	452	76.1						–448
1+2+3=*Tt. fossil fuels (10^3 toe)*	**1,907**	34.2						–1,257
4 CO_2 emissions (10^3 tonnes)	5,548	34.4						–3,702
5 Employment (10^3 FTE)	265	16.2						–27
Rest of the World	International Imports							***International***
1 Oil and derivatives (10^3 toe)	546	18.2						114
2 Natural Gas (10^3 toe)	765	38.8						–582
3 Coal (10^3 toe)	140	23.6						–130
1+2+3=*Tt. fossil fuels (10^3 toe)*	**1,451**	26.0						–598
4 CO_2 emissions (10^3 tonnes)	4,132	25.6						–1,661
5 Employment (10^3 FTE)	347	21.2						–141
Total	***Consumption responsibility***							***Total***
1 Oil and derivatives (10^3 toe)	**3,005**							–59
2 Natural Gas (10^3 toe)	**1,973**							–1,218
3 Coal (10^3 toe)	**594**							–578
1+2+3=*T. fossil fuels (10^3 toe)*	**5,572**							–1,855
4 CO_2 emissions (10^3 tonnes)	**16,140**							–5,363
5 Employment (10^3 FTE)	**1,636**							–168

higher than those with respect to the fuels embodied in Lisbon's production exports (to satisfy the demand of the Rest of Portugal and of the Rest of the World) $(460 + 660 = 1,120 \times 10^3$ toe, $186 + 183 = 369 \times 10^3$ toe and $4 + 10 = 14 \times 10^3$ toe, for oil, natural gas and coal, respectively), thus revealing (alike in the Sao Paulo case) a negative "primary energy trade balance" (with the exception of oil and derivatives (114×10^3 toe) with regard to international trade only).

In respect of CO_2 emissions, in 2010, Lisbon's territorial responsibility was $6,460 \times 10^3$ tonnes. Furthermore, the main results obtained for CO_2 emissions with regard to Lisbon's import and export of non-primary energy goods and services are in accordance with those found for the energy requirements. Indeed, incorporating the flows of international trade in the analysis, one can notice that, e.g. the emissions that occurred in Lisbon in satisfying (Rest of Portugal and international) foreign final demand ($1,846 + 2,471 = 4,317 \times 10^3$ tonnes) were smaller than the emissions that occurred outside of the region in satisfying the Lisbon residents' final demand ($5,548 + 4,132 = 9,680 \times 10^3$ tonnes), which means that Lisbon faced a negative "CO_2 emissions trade balance", or in other words, the Lisbon metropolitan area consumption-based responsibility ($16,140 \times 10^3$ tonnes) was substantially higher than its production-based responsibility ($10,777 \times 10^3$ tonnes). Furthermore, the estimated figures for emissions embodied in international imports (25.6% and 22%, for Lisbon and Sao Paulo metropolitan areas, respectively) are lower than the average of 40% of the total emissions embodied in countries' final demands, found by Andrew *et al.* (2009), using an MRIO model based on the dataset provided by the Global Trade Analysis Project (GTAP).

In terms of employment, it is estimated that the Lisbon metropolitan area territorial responsibility corresponds to $1,024 \times 10^3$ FTE jobs. It is also relevant to note that Lisbon metropolitan area's trade flows generate an "unfavourable" situation in terms of local employment, as the number of jobs embodied in its (interregional and international) exports (444×10^3 FTE) is lower than the level of employment that would be created in the Lisbon metropolitan area to satisfy its inhabitants' final demand, if their consumption from the Rest of Portugal and the Rest of the World (612×10^3 FTE) were to be replaced with domestically produced goods and services. Actually, assuming the Lisbon metropolitan area technology and productivity, there are about 265×10^3 FTE jobs in the Rest of Portugal and 347×10^3 FTE jobs in the Rest of the World that are "justified" for the production of goods and services that are to be consumed by Lisbon's inhabitants.

From the comparative analysis of the two case studies, and particularly in regard to interregional trade, it is relevant to highlight that the Lisbon metropolitan area is less dependent on Portugal than Sao Paulo is on Brazil. For example, 17.5% of the primary energy needs and 17.1% of the CO_2 emissions that are embodied in the Lisbon metropolitan area's production occur in satisfying the final demand of the other Portuguese people, while the final demand of the other Brazilians accounts for 50.8% and 51.3% of the Sao Paulo metropolitan area's energy requirements and CO_2 emissions, respectively. Furthermore, the satisfaction of Sao Paulo's final demand entails that 50.9% of the CO_2 emissions embodied correspond to production that occurs in the Rest of Brazil, while the Rest of Portugal produces goods and services that embody 34.4% of the emissions associated with the satisfaction of Lisbon's final demand. With regard to the metropolitan areas' international trade, the relative weights are, in general, more comparable.

In both cases, the metropolitan area's consumption-based responsibility is higher than its production-based responsibility with regard to both total fossil fuel needs and CO_2 emissions, though with substantially higher differences for the Lisbon case. This result is to be expected, if we consider Peters and Hertwich (2008), who estimated that in most developed countries (Annex B countries) production-based emissions are smaller than their consumption-based emissions. Nevertheless, the opposite result has also been found in some case specific studies. According to Choi (2015), in Atlanta, San Francisco and Seattle, the contribution to GHG emissions of their production to exports was estimated to be larger than the one of other's production to satisfy their metropolitan's areas imports. For New Zealand, Andrew and Forgie (2008) also found the consumer-based to be lower than the production-based responsibility. Summing up, the analysis of these flows, which include international trade, are thus critical to understand the impacts of changes in regions/countries' consumption and production, as many of the environmental impacts generated by consumption do not occur within each region's/country's borders (Hewings *et al.*, 2001; Peters *et al.*, 2011; Ramrattan and Szenberg, 2007; Stern, 2008). Actually, this research demonstrates the importance of using environmentally extended MIRO models to obtain a more comprehensive understanding of metropolitan areas' responsibility for energy requirements and CO_2 emissions (Ferreira *et al.*, 2018; Su *et al.*, 2010). Our results for the two case studies considered show that pressures on a specific city/region/country to meet tight limits in terms of GHG emissions might result in the region being tempted to reduce their GHG emissions "artificially", mostly by stopping the production of certain (energy and CO_2 intensive) goods and importing them from other regions/countries not party to agreements/commitments to limit GHG emissions. This would lead to the production of such goods in ways that are less environmentally sound (a phenomenon often designated as "carbon leakage"), which is contrary to the aims of the Kyoto Protocol and the Paris Agreement (Andrew and Forgie, 2008).

Furthermore, in the hypothetical scenario where (interregional and international) imports of non-energy goods and services are replaced with domestic production and (interregional and international) exports with domestic demand, to satisfy the same total levels of production and final demand, the Lisbon metropolitan area would have more employment (about 168×10^3 FTE jobs), but the trade-off would be the need to consume more energy (nearly $1,855 \times 10^3$ toe of fossil fuels) and the generation of more $5,363 \times 10^3$ tonnes of CO_2 emissions. On the other hand, in a similar scenario, the Sao Paulo metropolitan area would have 235×10^3 FTE less jobs, more CO_2 emissions and a higher level of fossil fuel use. In other words, the current situation in Sao Paulo, with interregional and international trade flows, is favourable both with regard to the environment and employment.

It is noteworthy that although detailed analysis was beyond the scope of this work, it was shown here that the use of the IO framework also allows for the consideration of a more explicit analysis of the impacts on employment of structural changes resulting from energy and/or environmental policies. Indeed, the analysis of the existing links between these "dimensions" allows for, e.g. the examination of the (net) number of jobs created or destroyed in an economy or in particular activity sectors, as a result of specific policy measures.

In summary, the results of the analysis of territorial, production and consumption-based responsibilities with regard to employment, primary energy and CO_2 emissions for the Sao Paulo and Lisbon metropolitan areas clearly support the "value-added" that the environmentally extended MRIO technique may bring to sustainability policy analysis (Hayami and Nakamura, 2007; Llop, 2007; Tunc *et al.*, 2007). Further, these results make clear the need for significant changes regarding the discussion of climate change policies on a subnational scale, namely regarding policy concertation and coordination at the global, national and subnational levels (Gonzalez *et al.*, 2011; Peters and Hertwich, 2008; Rootes *et al.*, 2012). Getting the appropriate governance structures in place is paramount to the success of effective environmental policies. Global and/or national strategies have to look at metropolitan/city scale actions as a key component and this certainly requires appropriate tools to help policymakers in the (*ex ante* and/or *ex post*) appraisal of the energy–economy–environment interactions between regions, within the same country and/or in other countries.

Conclusions

This research environmentally extended MRIO modelling framework and the corresponding estimations of energy–economy–environment multisectoral and multiregional interactions, illustrate the multiple traps and misconceptions that policy makers have to face in the context of climate change treaties and GHG emission threshold accomplishment, as they typically do not fully consider the possibility that some regions or countries may be tempted to reduce their GHG emissions "artificially", mostly by stopping the production of certain (energy and CO_2 intensive) goods and importing them from other regions.

The empirical analysis of the Sao Paulo and Lisbon metropolitan areas cases can be considered as distinctive illustrations of this hypothesis. Indeed, according to the calculations in this research, of the total CO_2 emissions that are embodied in production activities (both in Sao Paulo and Lisbon metropolitan areas), only a fraction corresponds to the satisfaction of local consumers' needs. On the other hand, to satisfy the demand of Sao Paulo and Lisbon consumers, just about 1/3 of the CO_2 emissions are embodied in the production that occurs in these regions. Overall, for both metropolitan areas, we have estimated less embodied CO_2 emissions considering production than consumption-based responsibilities.

The model approach and the results obtained for consumption *versus* production-based responsibility clearly reinforce the need to consider climate change policy actions directed towards consumers and their behaviour. Furthermore, actions directed to the production/technology side should take into account the identification of the value chain, not only in terms of inter-industry interaction, but also in regard to their location, so that policy measures can be effectively adapted to the territories. More than ever, there is a need for multilateral, national and metropolitan/city administrations to work together, and to think of cities not as a series of discrete activities but as a constellation of systems, with policies and regulations in place that take that into account. Indeed, such an economy-environment integrated emissions estimation approach might decisively help policy makers and practitioners to concentrate their attention and resources towards more impactful and effective emissions mitigation efforts.

Finally, the analysis reveals that the consideration of interregional interactions and leakages to other regions/countries, as well as the appraisal of eventual trade-offs between socio-economic and environmental targets, are critical for climate change policy's definition and monitoring. Accordingly, effectiveness of climate change policies on a subnational scale certainly calls for policy concertation and coordination at the global, national and subnational levels.

Acknowledgements

This work has been carried out under the *Energy for Sustainability Initiative* of the University of Coimbra and supported by Fundação para a Ciência e a Tecnologia under Post-Doctoral Grant (SFRH/BPD/115133/2016).

References

Alagoas (2012). *Balanco Energético do Estado de Alagoas: Ano Base 2011*. Secretaria de Estado do Planejamento e do Desenvolvimento Econômico, Maceió.

Almeida, T, L Cruz, E Barata and I-M García-Sánchez (2017). Economic growth and environmental impacts: An analysis based on a composite index of environmental damage. *Ecological Indicators*, 76, 119–130.

Andrew, R and V Forgie (2008). A three-perspective view of greenhouse gas emission responsibilities in New Zealand. *Ecological Economics*, 68, 194–204.

Andrew, R, G Peters and J Lennox (2009). Approximation and regional aggregation in multi-regional input-output analysis for National Carbon Footprint Accounting. *Economic Systems Research*, 21, 311–335.

Azzoni, C (2013). Concentration and inequality across Brazilian regions. In *Regional Problems and Policies in Latin America*, J Cuadrado-Roura and P Aroca (eds.), Advances in Spatial Science, Chapter 10, pp. 225–241. Berlin Heidelberg: Springer.

Bahia (2009). *Balanco Energético da Bahia 2009*. Secretaria de Infra-Estrutura — Coordenação de Desenvolvimento Energético, Salvador.

Baldwin, R (2006). *Globalization: The Great Unbundling(s)*. In Globalisation Challenges for Europe, Secretariat of the Economic Council (Ed.), Chapter 1, pp. 11–54. Finnish Prime Minister's Office Publications 18/2006, Helsinki.

Baynes, T, M Lenzen, J Steinberger and X Bai (2011). Comparison of household consumption and regional production approaches to assess urban energy use and implications for policy. *Energy Policy*, 39, 7298–7309.

Campos, I, J Guerra, J Ferreira-Gomes, L Schmidt, F Alves, A Vizinho and G Penha-Lopes (2017). Understanding climate change policy and action in Portuguese municipalities: A survey. *Land Use Policy*, 62, 68–78.

Carvalho, T and F Perobelli (2009). Avaliação da intensidade de emissões de CO_2 setoriais e na estrutura de exportações: um modelo inter-regional de insumo-produto Sao Paulo/restante do Brasil. *Economia Aplicada*, 13, 99–124.

Carvalho, T, F Santiago and F Perobelli (2013). International trade and emissions: The case of the Minas Gerais state — 2005. *Energy Economics*, 40, 383–395.

Ceará (2008). *Balanço Energético do Estado do Ceará*. Secretaria da Infra-Estrutura, Fortaleza.

Choi, T (2015). Understanding environmental responsibility of cities and emissions embodied in trade. *Economic Systems Research*, 27(2), 133–153.

Cruz, L and E Barata (2011). Hybrid IO analysis of CO_2 emissions: An application to the Portuguese Economy. In *Air Pollution: Economic Modelling and Control Policies*, L Llop (ed.), Environmental Sciences Series, Chapter 5, pp. 65–95. Bentham Science Publishers, Sharjah, U.A.E.

Cruz, L and J Dias (2016). Energy and CO_2 intensity changes in the EU-27: Decomposition into explanatory effects. *Sustainable Cities and Society*, 26, 486–495.

Cruz, L, P Ramos, E Barata and A Sargento (2017). Assessing an Agri-food development strategy: A bi-regional input-output model with resource-constrained sectors. *European Review of Agricultural Economics*, 44(5), 860–882.

DGEG (2013). *Energy Balance 2010*, Directorate General for Energy and Geology, Lisbon, Portugal.

Dietzenbacher, E, J Pei and C Yang (2012). Trade, production fragmentation, and China's carbon dioxide emissions. *Journal of Environmental Economics and Management*, 64(1), 88–101.

EPE (2009). *Balanço Energético Nacional 2009: Ano Base 2008*. Empresa de Pesquisa Energética — Ministério de Minas e Energia, Rio de Janeiro.

Espírito Santo (2013). *Balanço Energético do Estado do Espírito Santo: Ano Base 2012*. Secretaria de Estado de Desenvolvimento, Vitória.

Ferreira, J-P, E Barata, P Ramos and L Cruz (2014). Economic, social, energy and environmental assessment of inter-municipality commuting: The case of Portugal. *Energy Policy*, 66, 411–418.

Ferreira, J-P, P Ramos, L Cruz and E Barata (2017). Modeling commuting patterns in a multi-regional input-output framework: Impacts of an 'urban re-centralization' scenario. *Journal of Geographical Systems*, 19(4), 301–317.

Ferreira, J-P, P Ramos, L Cruz and E Barata (2018). The opportunity costs of commuting: The value of a commuting satellite account framework with an example from Lisbon Metropolitan Area. *Economic Systems Research*, 30(1), 105–119.

Forum Clima (2012). *O Desafio da Harmonização das Políticas Públicas de Mudanças Climáticas*. Fórum Clima — Ação Empresarial sobre Mudancas Climáticas, Instituto Ethos de Empresas e Responsabilidade Social, Sao Paulo.

Gibson, R (2006). Beyond the pillars: Sustainability assessment as a framework for effective integration of social, economic and ecological considerations in significant decision-making. *Journal of Environmental Assessment Policy and Management*, 8(3), 259–280.

Goiás (2009). *Balanco Energético do Estado de Goiás — BEGO 2009*. Secretaria de Estado de Infraestrutura, Goiânia.

Gonzalez, A, A Donnelly, M Jones, J Klostermann, A Groot and M Breil (2011). Community of practice approach to developing urban sustainability indicators. *Journal of Environmental Assessment Policy and Management*, 13(4), 591–617.

Guilhoto, J and U Sesso Filho (2005). Estimação da Matriz Insumo-Produto a Partir de Dados Preliminares das Contas Nacionais. *Economia Aplicada*, 9(2), 277–299.

Guilhoto, J and U Sesso Filho (2010). Estimação da Matriz Insumo-Produto Utilizando Dados Preliminares das Contas Nacionais: Aplicação e Análise de Indicadores Econômicos para o Brasil em 2005. *Economia & Tecnologia*, 6(23), 53–62.

Guilhoto, J, C Junior, J Visentin, D Imori and K Ussami (2017). Construção da Matriz Inter-regional de Insumo-produto para o Brasil: Uma aplicação do TUPI. Department of Economics, University of São Paulo, *TD NEREUS 03-2017*.

Hayami, H and M Nakamura (2007). Greenhouse gas emissions in Canada and Japan: Sector-specific estimates and managerial and economic implications. *Journal of Environmental Management*, 85(2), 371–392.

Hewings, G, Y Okuyama and M Sonis (2001). Economic interdependence within the Chicago Metropolitan Area: A Miyazawa analysis. *Journal of Regional Science*, 41, 195–217.

Hilgemberg, E and J Guilhoto (2006). Uso de combustíveis e emissões de CO_2 no Brasil: Um modelo inter-regional de insumo-produto. *Nova Economia*, 16(1), 49–99.

Hoekstra, A and T Wiedmann (2014). Humanity's unsustainable environmental footprint. *Science*, 344(6188), 1114–1117.

IBGE (2014). Contas Regionais do Brasil — 2012. Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brasil.

IBGE (2018). *Statistical Data (Database).* Brazilian Institute of Geography and Statistics, Rio de Janeiro, Brazil.

Ichihara, S, J Guilhoto and D Imori (2013). Regional development and government income transfer programs: Combining input–output systems and geoprocessing as tools for planning in São Paulo State, Brazil. In *Geography, Institutions and Regional Economic Performance*, R Crescenzi and M Percoco (eds.), Advances in Spatial Science, pp. 415–436. New York: Springer.

Imori, D, J Guilhoto and C Waisman (2018). Regional development and greenhouse gas emissions: The case of the Amazon region. *The Singapore Economic Review*, 63(2), 483–512.

INE (2018). *Statistical Data (database).* Statistics Portugal, Lisbon, Portugal.

INE (2012a). *Portuguese National Accounts 2010 (Base 2006).* Statistics Portugal — National Accounts, Lisbon, Portugal.

INE (2012b). *Portuguese Regional Accounts 2010 (Base 2006).* Statistics Portugal — Regional Accounts, Lisbon, Portugal.

IPCC (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Inventory Programme, H Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe (eds.). IGES, Japan.

Kronenberg, T (2009). Construction of regional input–output tables using nonsurvey methods: The role of cross-hauling. *International Regional Science Review*, 32(1), 40–64.

Lenzen, M, L Pade and J Munksgaard (2004). CO_2 multipliers in multi-region input–output models. *Economic Systems Research*, 16(4), 391–412.

Llop, M (2007). Economic structure and pollution intensity within the environmental input–output framework. *Energy Policy*, 35(6), 3410–3417.

Lucon, O and J Goldemberg (2010). Sao Paulo — The "Other" Brazil: Different pathways on climate change for state and federal governments. *The Journal of Environment & Development*, 19(3), 335–357.

Lutsey, N and D Sperling (2008). America's bottom-up climate change mitigation policy. *Energy Policy*, 36(2), 673–685.

Machado, G, R Schaeffer and E Worrell (2001). Energy and carbon embodied in the international trade of Brazil: An input–output approach. *Ecological Economics*, 39(3), 409–424.

Miller, R and P Blair (2009). *I-O Analysis: Foundations and Extensions*, 2nd edn. New York: Cambridge University Press.

Minas Gerais (2011). *26° Balanço Energético do Estado de Minas Gerais*. Superintendência de Tecnologia e Alternativas Energéticas — Companhia Energética de Minas Gerais, Belo Horizonte.

MCTI (2010). *Inventário Brasileiro de Emissões Antrópicas por Fontes e Remoções por Sumidouros de Gases de Efeito Estufa não Controlados pelo Protocolo de Montreal*. Ministry of Science, Technology and Innovation, Brasília.

Montoya, M, R Lopes and J Guilhoto (2014). Desagregação Setorial do Balanço Energético Nacional. *Economia Aplicada*, 18(3), 379–419.

Morrison-Saunders, A and R Therivel (2006). Sustainability integration and assessment. *Journal of Environmental Assessment Policy and Management*, 8(2), 281–298.

Muñoz, P and K Steininger (2010). Austria's CO_2 responsibility and the carbon content of its international trade. *Ecological Economics*, 69(10), 2003–2019.

Pablo-Romero, M, L Cruz and E Barata (2017). Testing the transport Energy Environmental Kuznets Curve hypothesis in the EU27 countries. *Energy Economics*, 62(1), 257–269.

Paraná (2011). *Balanço Energético do Paraná: 1980/2009*. Companhia Paranaense de Energia, Curitiba.

Peters, G and E Hertwich (2008). CO_2 embodied in international trade with implications for global climate policy. *Environmental Science & Technology*, 42(5), 1401–1407.

Peters, G, J Minx, C Weber and O Edenhofer (2011). Growth in emission transfers via international trade from 1990 to 2008. Proceedings of the National Academy of Sciences, 108(21), 8903–8908.

Puppim de Oliveira, J (2009). The implementation of climate change related policies at the subnational level: An analysis of three countries. *Habitat International*, 33(3), 253–259.

Ramos, P, L Cruz, E Barata, A Parreiral and J-P Ferreira (2015). A Bi-Regional (Rectangular) Input-Output Model for Portugal: Centro and Rest of the Country. In *Assessment Methodologies: Energy, Mobility and Other Real World Applications*, P Godinho and J Dias (eds.), Ch. 12, pp. 265–285. Coimbra: Imprensa da Universidade de Coimbra.

Ramrattan, L and M Szenberg (2007). The influence of international trade on the environment. *Journal of Environmental Assessment Policy and Management*, 9(2), 235–271.

Rio de Janeiro (2013). *Balanço Energético do Rio de Janeiro 2013: Ano Base 2012.* Secretaria de Estado de Desenvolvimento Econômico — Energia, Indústria e Serviços, Rio de Janeiro.

Rio Grande do Sul (2010). *Balanço Energético do Rio Grande do Sul 2010: Ano base 2009*. Secretaria de Infra-Estrutura e Logística, Porto Alegre.

Romeiro, V and V Parente (2011). Climate change regulation in Brazil and the role of subnational governments. In *Climate Change in Brazil: Economic, Social and Regulatory Aspects*, R Seroa da Motta, J Hargrave, G Luedemann and M Gutierrez (eds.), Ch. 2, pp. 45–57. Brasilia: Ipea.

Rootes, C, A Zito and J Barry (2012). Climate change, national politics and grassroots action: An introduction. *Environmental Politics*, 21(5), 677–690.

Sao Paulo (2009). *Balanço Energético do Estado de Sao Paulo 2009: Ano Base 2008*. Secretaria de Saneamento e Energia — Coordenadoria de Energia, Sao Paulo.

Sargento, A, P Ramos and G Hewings (2011). Input–output modeling based on total-use rectangular tables: Is this a better way? *Notas Económicas*, 34, 8–34.

Schreurs, M (2008). Local and subnational climate change politics. *The Journal of Environment & Development*, 17(4), 342–355.

Somanathan, E, T Sterner, T Sugiyama, D Chimanikire, N Dubash, J Essandoh-Yeddu, S Fifita, L Goulder, A Jaffe, X Labandeira, S Managi, C Mitchell, J Montero, F Teng, and T Zylicz (2014). National and Sub-national Policies and Institutions. In *Climate Change 2014: Mitigation of Climate Change — Contribution of Working Group III to the Fifth Assessment Report of the IPCCC*, O Edenhofer *et al.* (eds.). Cambridge University Press, Cambridge.

Stern, N (2008). *The Economics of Climate Change: The Stern Review*. Cambridge: Cambridge University Press.

Su, B, H Huang, B Ang, P Zhou (2010). Input–output analysis of CO_2 emissions embodied in trade: The effects of sector aggregation. *Energy Economics*, 32(1), 166–175.

Timmer, M, A Erumban, B Los, R Stehrer and G de Vries (2014). Slicing up global value chains. *The Journal of Economic Perspectives*, 28(2), 99–118.

Tunc, G, S Turut-Asik and E Akbostanci (2007). CO_2 emissions vs. CO_2 responsibility: An input-output approach for the Turkish economy. *Energy Policy*, 35(2), 855–868.

UN-Habitat (2016). *Urbanization and Development: Emerging Futures — World Cities Report 2016*. Nairobi, Kenya: United Nations Human Settlements Programme (UN-Habitat).

Wei, T and Z Tang (2014). Building low-carbon cities: Assessing the fast growing U.S. cities' land use comprehensive plans. *Journal of Environmental Assessment Policy and Management*, 16(1), 1–28.

Wiebe, K, M Bruckner, S Giljum and C Lutz (2012). Calculating energy-related CO_2 emissions embodied in international trade using a global input-output model. *Economic Systems Research*, 24(2), 113–139.

Wiedmann, T (2009). A review of recent multi-region input-output models used for consumption-based emission and resource accounting. *Ecological Economics*, 69(2), 211–222.