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Decomposition of CO_2 emissions change from energy consumption in Brazil: Challenges and policy implications

Luciano Charlita de Freitas *, Shinji Kaneko

Graduate School for International Development and Cooperation, Development Policy, Hiroshima University 1-5-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8529, Japan

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ABSTRACT

This study evaluates the changes in CO_2 emissions from energy consumption in Brazil for the period 1970–2009. Emissions are decomposed into production and consumption activities allowing computing the full set of energy sources consumed in the country. This study aims to develop a comprehensive and updated picture of the underlying determinants of emissions change from energy consumption in Brazil along the last four decades, including for the first time the recently released data for 2009. Results demonstrate that economic activity and demographic pressure are the leading forces explaining emission increase. On the other hand, carbon intensity reductions and diversification of energy mix towards cleaner sources are the main factors contributing to emission mitigation, which are also the driving factors responsible for the observed decoupling between CO_2 emissions and economic growth after 2004. The cyclical patterns of energy intensity and economy structure are associated to both increments and mitigation on total emission change depending on the interval. The evidences demonstrate that Brazilian efforts to reduce emissions are concentrated on energy mix diversification and carbon intensity control while technology intensive alternatives like energy intensity has not demonstrated relevant progress. Residential sector displays a marginal weight in the total emission change.

1. Introduction

The 2009 United Nations Climate Change Conference is the latest reference on global efforts toward climate change mitigation initiatives. Despite the failure in establishing a binding target for global emissions, analysts have celebrated the effective integration of countries such as Brazil, China, India and South Africa into the debate of greenhouse gas (GHG) emissions reduction. In summary, transition countries as China, India and Brazil recognized their importance in the global warming theme announcing pledges on domestic emissions reduction (Richardson et al., 2009; UNFCCC, 2010).

Brazil's pledge consisted on a voluntary commitment to reduce CO_2 emissions to 36.1–38.9% of values expected to be emitted by 2020 under business as usual conditions (Brazil, 2009; Cenbio, 2009). This target splits the international audience into enthusiastic supporters founded on the paradigmatic introduction of renewable resources in the Brazilian energy matrix and the active role of the country in the international dialog on climate change and a group of skeptics that were suspicious of Brazil's capacity to combine economic development while reducing emissions.

One amongst others sources of skepticism toward Brazilian proposal is the partial understanding of the factors causing emissions change in the country, an issue that goes beyond the general discussion on fuel diversification and deforestation control presented by Brazilian authorities (MCT, 2008, 2009). Similarly, suspicions exist regarding issues such as the negligence of modern environment-friendly energy sources and uses and the historical failure to decouple economic growth and emissions, among others (Gouvello, 2010). Furthermore, specialists have called attention to the incipient regulation framework and fragmented legal apparatus available to emissions reduction enforcement (Seroa da Motta, 2010a, 2010b; Serra, 2010).

In practice, current estimates by the International Energy Agency's (IEA) place Brazil in fifth position in the ranking of GHG emissions (IEA, 2009), with emissions from energy consumption being an issue of particular concern (IEA, 2009; MCT, 2009). Figures from the 2009 Brazilian Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases show that energy consumption-induced CO_2 emissions are the second major source of GHG emissions in Brazil, after land-use change and forestry-related emissions, with growth of more than 70% from 1990 to 2005 (MCT, 2009). The evidences become dramatic when it is taken into consideration the perspectives of economic growth with energy-intensive sectors assuming a major stake in the economic development plan (Brazil, 2010).

* Corresponding author. Tel./fax: +81 090 2867 8995.
E-mail address: lucianofreitas@hiroshima-u.ac.jp (L.C. de Freitas).

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This study aims to develop a comprehensive and updated picture of the underlying determinants of emissions change from energy consumption in Brazil. Evaluation is proposed within a log-mean Divisia index (LMDI) framework and includes observations during the period 1970–2009. CO_2 emissions are estimated according to IPCC guidelines (IPCC, 2006) while underlying determinants are selected based on the previous studies reviewed below. Decomposition of emissions is proposed at two levels, production activities and consumption activities, i.e. industry, energy generation, service and public sectors, agriculture and feedstock, transportation and household emissions. This combination of sectors and fuel mix accounts for all energy consumption in Brazil allowing a full evaluation of national emissions change decomposition. The aggregated results for the national level are compared with previous studies on Brazil while the recently released data for 2009 offers an updated view on recent trends carried out under a scenario of world economic crisis and environmental concerns.

Within the proposed framework, specific attention is paid to the transformation of the Brazilian energy mix. The importance of this aspect relates to the undeniable relevance of Brazilian energy switching as the main component of national emissions mitigation efforts (MCT, 2008). Therefore, the selected period involves both the consolidation of hydropower generation and the introduction of sugarcane energy by-products that ultimately allowed a qualitative transformation of the national energy matrix with an influential impact on electricity generation and liquid fuel diversification (Tolmasquim et al., 2007).

The remainder of this article is organized into three sections. Section 2 examines the characteristics of the Brazilian energy matrix and its evolution since 1970. A brief introduction to the policies underlying fuel shifting and its incorporation into the national energy matrix is included. Section 3 presents the methodological aspects, data sources, and limitations of the study. The results and discussions are presented in Section 4, with main conclusions highlighted in Section 5.

2. Trends and distinctive aspects of the Brazilian energy matrix and introductory notes on emission change studies

The Brazilian energy matrix is characterized by a peculiar combination of fossil fuels and renewable energy sources. Table 1 summarizes the main components of the Brazilian energy mix according to the data provided by the Ministry of Mining and Energy through the Brazilian Energy Research Company (EPE, 2010). From the data it is noticeable that during the last four decades approximately half of the energy consumed in Brazil consisted of oil derivatives and their share in the total energy matrix experienced little change from 1970. The other half is composed of renewable sources, which have experienced systematic transformation in the last 40 years when biomass was replaced by hydropower and sugarcane energy derivatives.

Table 1 also shows the consistent increase in energy consumption in Brazil. During the period 1970–2009, energy consumption increased 256.4% with remarkable growth in energy production from hydropower and by-products of sugarcane. Fig. 1 illustrates the total energy consumption by sector from 1970 to 2009.

From Fig. 1 it is noticeable that all sectors experienced increases in energy consumption. The exception to the general trend is the household sector, which presented reductions in energy consumption in the period between 1980 and 1999 before consumption increased in the final decade to a level close to that in the period 1970–1979. The justification for such a pattern is the substitution of conventional energy sources like firewood with more efficient sources such as liquefied petroleum gas (LPG) and electricity between 1984 and 1994 (EPE, 2010).

The composition of energy consumption by sector is another issue of major importance. A detailed summary of the fuel share by sector is provided further in Table 3. Anticipating some examples for readers' reference, the robust increment of energy consumption from hydropower is notable, e.g. while in 1970 only 3% of energy consumed by the household sector came from hydropower, in 2009 this percentage reached 38% (EPE, 2010). Likewise, while the usage of sugarcane cogenerated electricity accounted for 6% of total fuel in 1970, the share reached 51% in 2009. Finally, the virtually nonexistent ethanol in 1970 assumed a 19% share in 2009 (EPE, 2010).

The successful introduction of hydropower and sugarcane energy by-products in the national energy mix is a result of various factors that highlights the pragmatism of policies in the energy sector. Hydropower was originally projected to offer stable electricity supply to the expanding industrial sector and urban areas from major projects in the 1960s and 1970s (Brazil, 2007). Major facilities were developed with government resources and afterwards operated as government-controlled public companies (Araujo and Ghirardi, 1987; Szklo and Cunha, 2006). In contrast, the sugarcane energy by-products are essentially private projects triggered by policy-oriented initiatives (Goldemberg and Moreira, 2005).

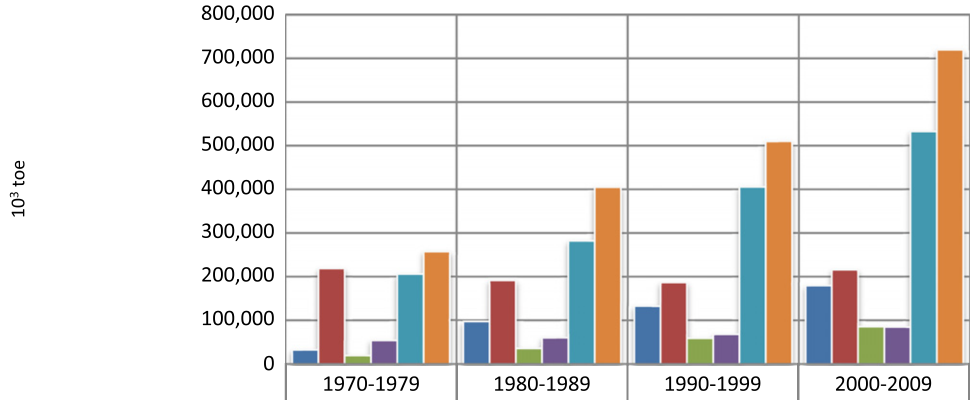
The development of sugarcane energy by-products is worth additional discussion. The sugarcane industry is of historical importance in the economic development of Brazil and the successful conversion of raw material into energy by-products turned the culture of sugarcane into one of the main engines of progress in Brazilian agribusiness. One of the main energy by-products of sugarcane is ethanol, which has performed an important role in reshaping the market for liquid fuels in Brazil (Goldemberg and Moreira, 2005; EPE, 2010).

Equally important, although less popular, is the usage of sugarcane residuals for electricity cogeneration. Originally, sugarcane residuals were used as fuel for steam boilers within ethanol facilities and attached industrial units being further integrated into the electricity grid and commercialized through agreements with electricity suppliers (Coelho and Bolognini, 1999; Scaramucci et al., 2006). Among the motivations behind such an initiative is the

Table 1
Energy mix by source consumed in Brazil (1970–2009) 10^3 toe (% of total).
Source: EPE, 2010.

Sources	1970–1979	1980–1989	1990–1999	2000–2009
Oil derivatives	397,194 (48%)	509,288 (44%)	690,827 (47%)	856,777 (44%)
Biomass[a]	284,134 (35%)	255,202 (22%)	188,206 (13%)	209,436 (11%)
Sugarcane derivatives	49,188 (6%)	144,041 (13%)	212,943 (14%)	295,708 (15%)
Hydropower	60,385 (7%)	142,367 (12%)	225,610 (15%)	318,119 (16%)
Other nonrenewables	27,815 (3%)	90,174 (8%)	135,345 (9%)	235,539 (12%)
Other renewables	2971 (0%)	10,945 (1%)	21,629 (1%)	42,056 (2%)

[a] Except sugarcane biomass; toe refers to tons of oil equivalent.



	1970-1979	1980-1989	1990-1999	2000-2009
Energy	32,248	97,376	132,668	179,549
Household	218,646	191,698	186,740	215,930
Service and Public	19,595	35,911	59,256	85,538
Agriculture and Feedstock	54,040	60,280	68,045	84,619
Transport	205,872	281,938	405,491	532,460
Industry	257,777	405,182	509,878	719,807

Fig. 1. Evolution of energy consumption by sector in the Brazilian economy.
Source: EPE, 2010.

immediate demand from ethanol producers, normally located non-electrified rural areas, the expected financial gains under the framework of the Clean Development Mechanism and the institutional support introduced within the Alternative Energy Sources Incentive Program (Proinfa) whose main purpose is to encourage independent electricity producers to commercialize electricity surplus with local electrical operators (Brazil, 2004).

Proinfa is the latest attempt toward diversification of the energy matrix and is primarily a result of the hydroelectricity supply shortage, labeled by Brazilians as the "apagão", that extended from mid-2001 to the beginning of 2002 (Anuatti-Neto and Hochstetler, 2002). The program launched the foundations of regulatory framework and inceptives to the development of new renewable energy sources including the commercial usage of cogenerated electricity from biomass, photovoltaic and wind power projects (Dutra and Szklo, 2008). Apart from biomass usage, the program has produced only marginal results so far (EPE, 2010).

Notwithstanding the effective efforts in diversifying the energy mix along the last four decades, initiatives have fundamentally been divorced of concerns on environmental themes. A retrospect on the specific issue of energy diversification in Brazil indicates a systematic linkage between initiatives toward energy matrix diversification and events of supply shortage, some examples being the two oil shocks in the 1970s and the apagão in the beginning of 2000s (Anuatti-Neto and Hochstetler, 2002; Rosa et al., 2002). While the first events leveraged projects of hydropower production and the introduction of ethanol fuel, the apagão was a trigger for the latest initiative toward national energy matrix diversification, carried under the Proinfa.

Regarding the issue of global warming, the development of renewable energy sources in Brazil was not able to offset the growth in emission from fuel combustion (Rosa et al., 2006). Specific literature on the theme contrasts the benefits of energy mix and carbon intensity reduction with the risks of persistent linkage between economic growth and emission and the demographic pressures (Mendonça and Gutierez, 2000; Luukkanen and Kaivo-oja, 2002; Medeiros and Dezidera, 2006; Bacon and Bhattacharya, 2007; Kojima and Bacon, 2009). Next section offers a review on this discussion.

3. Literature review, methodology and data sources

3.1. Overview of decomposition studies on the Brazilian context

The remarkable growth of emissions from energy consumption poses important challenges to policy makers and energy consumers worldwide. In this context, understanding the determinants of emissions change is one of the fundamental reasons for the current popularity of decomposition studies.

The pioneering work by Grossman and Krueger (1991) adapted the decomposition method to the context of environmental studies. The authors decomposed CO_2 emissions change into economy scale, economy composition and technology factors, for the members of the North American Free Trade Agreement. Conclusion indicates that economic growth tends to alleviate pollution problems. Similarly, Torvanger (1991) evaluated emissions change in the industrial sectors of nine OECD countries in the context of cleaning efforts of manufacturing emissions associated with economic growth and increasing energy prices. Findings indicate that the main contribution to reduced carbon dioxide intensity comes from the reduction in manufacturing energy intensity.

Applications of decomposition models to developing countries started in the early 1990s. Studies by Ang and Lee (1994), Ang (1995), Shrestha and Timilsina (1996), Ang and Pandiyan (1997), Han and Chatterjee (1997), Ang et al. (1998), Sun and Malaska (1998), Sun (1998), Ang and Zhang (1999), Luukkanen and Kaivo-oja (2002), Paul and Bhattacharya (2004), Wu et al. (2005), Lee and Oh (2006) and Zhang et al. (2009) promoted the dissemination of the method and became major references in the formulation of energy and environmental policies. The method has also been supported by studies by the International Energy Agency (e.g. IEA/OECD, 2004) and the United States Department of Energy (e.g. DOE, 2003), among other major organizations, which have frequently based their reports and recommendations on the results of decomposition analysis.

In Brazil the method has only been explored partially and few applications are reported in the literature. The first identified study using decomposition in Brazil was developed by Seroa da Motta and Araujo (1989). The authors decomposed the demand for energy in the industrial sector in Brazil for the period 1973–1984 concluding that the shifting in the composition of production structure in the manufacturing sector did not affect the energy intensity in the sector. Worrell et al. (1997) decomposed the energy consumption in the iron and steel industry in selected countries concluding that, for the Brazilian case, energy consumption in this industry decreased with increments in the efficiency of energy usage.

Wachsmann et al. (2009) assessed the structural decomposition of energy use in the industrial and household sectors in Brazil from 1970 to 1996. Authors observed that energy usage by households is small compared with the changes in total energy consumed in Brazil, while the industry sector is the main contributor to growth in energy use. The authors concluded that the affluence effects of economic activity and population are the main determinants of energy use growth in Brazil, while the improvement in energy intensity and change in household energy usage are pointed to as factors contributing to decreased energy use. In Achão and Schaeffer (2009), the variation in energy consumption by household is explained among other reasons by government programs involving income transfers and the expansion of electricity distribution.

The first study on CO_2 emissions change developed to the Brazilian context is provided by Mendonça and Gutierez (2000). The authors evaluated CO_2 emissions for the energy sector in Brazil highlighting the deceleration of population growth and improving energy intensity as factors contributing to reduced emissions between 1970 and 1995. Medeiros and Dezidera (2006) first attempted to evaluate emissions change on a national and multi-sectorial scale. Their results indicated that economic activity has played a key role in the emissions change while the diversification of the energy matrix toward lower carbon intensity sources has contributed to alleviate pressure on emissions growth. Despite the importance of these studies, decomposition accuracy was disturbed by residuals and limited number of factors due to limitations of the employed method. Furthermore, the authors failed to account for emissions from energy consumption in the residential sector and faced limitations in the accounting of CO_2 emissions given the limitations of references available by that time.

Because of the relevance and peculiarities of Brazil's energy composition and emission pattern within the context of climate change, the country has also been subject to comparative studies by the international community. For example, Luukkanen and Kaivo-oja (2002) identified that, among other findings, compared with several other nations, the trend in carbon intensity in Brazil is associated with changes in the fuel composition. In other words, authors found that reduction of carbon intensity of energy consumption reflects the diversification of Brazilian energy mix towards clean sources. Machado and Schaeffer (2006) found that a significant part of the upward trend in overall energy intensity in Brazil is related to both economic restructuring toward low value-added and energy-intensive activities. Bacon and Bhattacharya (2007) pointed out that energy intensity in Brazil is a contributing factor toward higher emissions standards, while the observed performance of countries like Russia, India and China suggests that improvements in energy intensity have been the main factors for emissions reduction. Kojima and Bacon (2009) observed that the exceptional performance of energy mix in Brazil goes against the general decline in the weight of energy mix worldwide.

The study by Vehmas (2009) transcends the traditional set of contributing factors behind the change in CO_2 emissions from energy consumption. The author incorporates to the analysis factors built under a macroeconomic perspective and others closed to energy usage. Particularly to Brazil findings reveal that energy intensity of the whole economy and the share of economically active persons have a peculiar weight in increments of emission compared to the performance of other major developing nations. Within the national context changes in the amount of population plays the largest effect on emission growth.

Despite of the efforts by international community most available studies to Brazil are presented in a context of international comparison and the majority does not include references on domestic policies and recent updates. Furthermore, international studies rarely account for domestic data sources provided by public authorities, which ultimately transfer to the analysis the eventual approximations and generalizations embedded in international data sources.

Table 2 summarizes a sample of most referred decomposition studies addressing the issue of emission from energy consumption in Brazil and the main factors affecting changes in CO_2 emissions.

From the summary it is observed the remarkable weight of economic activity and population pressure as main factors driving emissions growth. Likewise, energy mix factor is pointed as the main factor contributing to emission mitigation.

3.2. Decomposition approach and model formulation

The abovementioned decomposition studies occurred in parallel to refinement of the methodology. An extensive survey by Ang and Zhang (2000) identified several decomposition studies showing major progress in the methodology along the time. Among other methods, the study identifies the LMDI along with the refined Laspeyres index as the most robust methods, the fact that these methods offer results free of residuals being remarkable (Ang and Liu, 2007). The preference for the LMDI by researchers and policy makers has, however, offset the application of the Laspeyres method in recent years (Ang, 2004).

The predilection for the LMDI reflects the embedded properties of the method, and the simplicity in the formulation and interpretation of results. Furthermore, the LMDI is based on robust theoretical foundations allowing consistency in the results both in

Table 2
Emission change decomposition studies in Brazil (sample).

Reference	Period	Level	Main emission increment factors in Brazil	Main emission mitigation factor in Brazil
Mendonça and Gutierez (2000)	1970–1990	Energy Sector	EA, EI	EM
Luukkanen and Kaivo-oja (2002)	1971–1999	International	EI	EM
Medeiros and Dezidera (2006)	1970–2004	National	EA	EM
Bacon and Bhattacharya (2007)	1994–2004	International	EI, P	CI
Kojima and Bacon (2009)	1994–2006	International	EA, P	ES
Vehmas (2009)	1990–2003	International	P	*

Notes: EA: economic activity; EI: energy intensity; CI: carbon intensity; EM: energy mix; ES: economy structure; P: population; *: Author did not identify numerical decrease in considered factor for Brazil.

additive and multiplicative forms (Ang, 2004). Consideration of the best method for this study was based on the nature of the proposed analysis, the characteristics of the dataset for the Brazilian case and the capacity of the model to decompose emissions into multiple determinants and consistently aggregate without major transformation in the calculation procedure (Ang and Liu, 2007). Therefore, the analysis proposed in this study is based on the LMDI proposed by Ang and Choi (1997) and refined by Ang et al. (1998) and Ang and Liu (2001).

Changes in CO_2 emissions are computed for 6 sectors and 19 energy sources. Each sector (i) consumed during the assessed period a specific set of final energy consumption by sources (j). Table 3 summarizes the combination of sectors and energy mixes considered in this study. The values in the table correspond to the share of each energy source consumed by sector during the assessed period.

Emission change is decomposed on a set of factors detailed in Table 4. Each factor has an explanatory weight in the decomposition model allowing generalizations to be made about the total emissions change for selected time intervals.

Carbon intensity corresponds to the ratio of carbon emissions and energy consumed during a particular period. The carbon intensity represents the quality of the energy mix consumed in the country in a given period. An energy mix composed of high embodied energy and low carbon contents would effectively contribute to lower emissions standards.

Energy mix refers to the change in energy composition during a particular period. It measures the effects of shifting patterns of fuel consumption from available energy sources. The energy mix ultimately reflects the effects of policies and consumer initiatives toward energy consumption diversification.

Energy intensity is the ratio of energy consumed and a measure of economic output by sector. The relevance of this measure relates to its capacity to offer an aggregate view of the performance of energy prices, fuel quality and the composition of the energy matrix, technology improvement and investment in clean and energy-saving technologies, and the fuel substitution effect.

The structural composition of the economy indicates the relative weight of the output of specific sectors relative in the value added of the overall economy. This incorporates into the model the relative impact of structural change in the economy on the final change in CO_2 emissions for a particular period.

Economy activity represents the overall performance of the economy. The factor is given as in GDP per capita and captures the income effect on CO_2 emissions change from energy consumption. Finally, population refers to the effects of population growth as a determinant of energy demand.

The residential sector, characterized as consumption activity, has different features compared to productive sectors and for this reason was computed separately in order to clarify the relative importance of the sector within the general context of CO_2 emissions in Brazil. Such composition allows a full evaluation of all the energy consumed in the country overcoming some of the limitations of previous studies. To the residential sector energy intensity factor is measured as the ratio of energy consumption and population resident while energy activity is

Table 3
Matrix of energy sources and final consumption by sector (1970–2009).

Energy source/sector	i_1: Industry	i_2: Energy	i_3: Agriculture & feedstock	i_4: Service & public	i_5: Transport	i_6: Residential
j_1: Biomass	26.48%	–	14.61%	0.69%	0.03%	58.19%
j_2: Charcoal	85.54%	–	0.21%	1.30%	–	12.95%
j_3: Coal	100.00%	–	–	–	–	–
j_4: Coal coke	99.99%	0.01%	–	–	–	–
j_5: Diesel	2.06%	1.06%	15.12%	0.74%	81.02%	–
j_6: Electricity	48.85%	3.58%	3.39%	21.44%	0.48%	22.27%
j_7: Ethanol	–	–	–	–	100.00%	–
j_8: Fuel oil	73.32%	13.51%	0.66%	3.16%	9.35%	–
j_9: Gas coke	55.49%	11.76%	–	8.12%	–	24.63%
j_{10}: Liquefied petroleum gases	7.03%	0.33%	0.12%	6.00%	–	86.53%
j_{11}: Motor gasoline	–	–	–	–	100.00%	–
j_{12}: Naphtha	84.34%	15.66%	–	–	–	–
j_{13}: Natural gas	57.33%	30.81%	0.02%	1.56%	8.94%	1.34%
j_{14}: Other kerosene	2.76%	0.07%	0.02%	0.12%	89.24%	7.78%
j_{15}: Other oil secondary sources	54.75%	45.19%	–	0.06%	–	–
j_{16}: Other primary sources	100.00%	–	–	–	–	–
j_{17}: Steam coal	98.82%	0.03%	–	–	1.15%	–
j_{18}: Sugarcane energy by-products	57.38%	42.62%	–	–	–	–
j_{19}: Tar	75.16%	24.84%	–	–	–	–
Total energy sources	17	13	8	10	9	7

Table 4
Variable definitions for emissions determinants.

Item	Item description	Determinant	Description
C_{ij}	CO_2 emission by fuel j in sector i	$\frac{C_{ij}}{E_{ij}}$	CI: Carbon intensity of production sectors; CIR: carbon intensity residential sector
E_{ij}	Energy consumption by fuel j in sector i		
E_i	Total energy consumption in sector i	$\frac{E_{ij}}{E_i}$	EM: Energy mix of production sectors; EMR: energy mix residential sector
Y_i	Output from sector i	$\frac{E_i}{Y_i}$	EI: Energy intensity of production sectors
Y	Total output of the economy given in real 2009 US$ GDP	$\frac{Y_i}{Y}$	ES: Economy structure
		P	P: Population
P	Population	$\frac{Y}{P}$	EA: Economic activity (real GDP per capita)
		$\frac{E_i}{P}$	EIR: Energy intensity in residential sector

excluded of the decomposition. Other factors follow the logic presented for the production activities sectors.

Within the decomposition framework, national CO_2 emissions are aggregated from emissions in the productive activities and residential sectors, and summarized according to the following additive function:

$$\begin{aligned} CO_{2_t} - CO_{2_{t-1}} &= \Delta CO_2 \\ &= \sum_{i=1}^{5}\sum_{j=1}^{19} \Delta CI_{ij} + \Delta EM_{ij} + \Delta EI_i + \Delta ES_i + \Delta EA + \Delta P \\ &\quad + \sum_{i=6}^{7}\sum_{j=1} \Delta CIR_{ij} + \Delta EMR_{ij} + \Delta EIR_i + \Delta PR \end{aligned} \tag{1}$$

The final decomposition equation is derived from the function specified in Eq. (1) according to the lessons by Ang and Liu (2001), Ang (2005) and Wu et al. (2005). Thus, the equation for emissions decomposition is presented as follows:

$$\begin{aligned} CO_{2_t} - CO_{2_{t-1}} \equiv & \left[\sum_{i=1}^{5}\sum_{j=1}^{19} \vartheta_{ij(t)} \ln\left(\frac{CI_{ij,t}}{CI_{ij,t-1}}\right)\right] + \left[\sum_{i=1}^{5}\sum_{j=1}^{19} \vartheta_{ij(t)} \ln\left(\frac{EM_{ij,t}}{EM_{ij,t-1}}\right)\right] \\ & + \left[\sum_{i=1}^{5}\sum_{j=1}^{19} \vartheta_{ij(t)} \ln\left(\frac{EI_{ij,t}}{EI_{ij,t-1}}\right)\right] + \left[\sum_{i=1}^{5}\sum_{j=1}^{19} \vartheta_{ij(t)} \ln\left(\frac{ES_{ij,t}}{ES_{ij,t-1}}\right)\right] \\ & + \left[\sum_{i=1}^{5}\sum_{j=1}^{19} \vartheta_{ij(t)} \ln\left(\frac{EA_{t}}{EA_{t-1}}\right)\right] + \left[\sum_{i=1}^{5}\sum_{j=1}^{19} \vartheta_{ij(t)} \ln\left(\frac{P_{t}}{P_{t-1}}\right)\right] \\ & + \left[\sum_{i=1}\sum_{j=1}^{7} \vartheta_{ij(t)} \ln\left(\frac{CIR_{ij,t}}{CIR_{ij,t-1}}\right)\right] + \left[\sum_{i=1}\sum_{j=1}^{7} \vartheta_{ij(t)} \ln\left(\frac{EMR_{ij,t}}{EMR_{ij,t-1}}\right)\right] \\ & + \left[\sum_{i=6}\sum_{j=1}^{7} \vartheta_{ij(t)} \ln\left(\frac{EIR_{i,t}}{EIR_{i,t-1}}\right)\right] + \left[\sum_{i=6}\sum_{j=1}^{7} \vartheta_{ij(t)} \ln\left(\frac{PR_{i,t}}{PR_{i,t-1}}\right)\right] \end{aligned} \tag{2}$$

The time intervals are denoted by t where $t \in [0,T]$. The analysis uses five-year intervals resulting in eight periods from 1970 to 2009. The choice of five-year intervals aims to capture changes in the energy mix and energy policies as well as the cyclical pattern of the Brazilian economy. The term $\vartheta_{ij}(t)$ operates as additive weight function estimated within the LMDI framework (Ang, 2005). The function is given by

$$\vartheta_{ij}(t) = \frac{CO_{2_{ij,t-1}} - CO_{2_{ij,t}}}{\ln CO_{2_{t-1}} - \ln CO_{2_t}} \tag{3}$$

There are two cases of zero values in the dataset for Brazil. The first case relates to the change in the use of naphtha, i.e. no use between 1985 and 1993 and in 2003, and eventual use in the other years. The second relates to the introduction of coal in the energy matrix after 1992. Such cases cause problems in the formulation of the decomposition because of the properties of logarithmic functions. In order to accommodate the zero value cases, the literature on the LMDI suggests replacing the zeros in the dataset by a small positive number (Ang et al., 1998; Muller, 2006; Ang and Liu, 2007).

3.3. Data sources, assumptions and limitations

This study assumes the same energy mix as classified in the National Energy Balance published yearly by the Brazilian Ministry of Mines and Energy (EPE, 2010). Fig. 2 refers to the structure of Brazilian energy balance including the composition of the final energy usage in Brazil.

This figure indicates that energy consumption is measured in terms of net values, or apparent consumption under the terminology of the IPCC (2006), originally presented in tons of oil equivalent (toe) in the National Energy Balance (EPE, 2010) and converted to terajoules (TJ) assuming an equivalence of 41,868 TJ/10^3 toe. Only final energy consumption is considered for calculations in order to avoid double counting.

Regarding the estimation of CO_2 emissions for the various energy sources, the methodology developed by the IPCC (2006) was taken into consideration. Fundamentally it consists of a straightforward application of carbon emissions for each fuel consumed with a correction for carbon unoxidized and subtraction of excluded carbon corresponding to the fraction of carbon in feedstock and nonenergy use excluded from fuel combustion emissions.

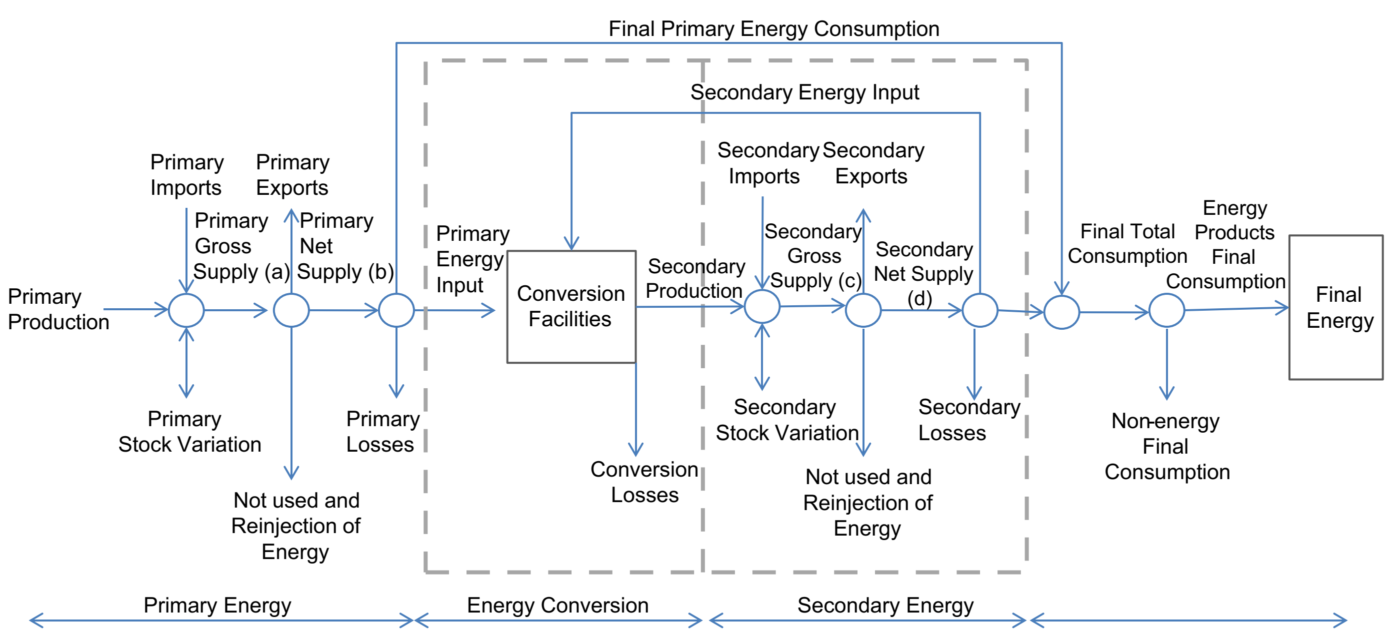


Fig. 2. General structure of the Brazilian energy balance.
Notes: (a) Primary gross supply refers to primary energy produced in the country plus imports; (b) primary net supply refers to primary energy available for domestic consumption after exports; similar logic is applied to (c) and (d).
Source: EPE, 2010 with adaptations by the authors.

Table 5
Energy sources for electricity generation in Brazil (1970–2009).

Fuel source	1970–1979	1980–1989	1990–1999	2000–2009
Hydraulic power (%)	90.6	92.1	91.5	83.1
Fuel oil (%)	5.1	2.1	1.5	1.4
Steam coal (%)	1.9	1.8	1.5	1.6
Sugarcane biomass (%)	0.8	0.9	1.0	2.0
Diesel (%)	0.7	0.9	1.2	1.7
Uranium (%)	0.0	0.5	0.8	3.1
Natural gas (%)	0.0	0.0	0.3	3.9
Other wastes (%)	0.4	0.7	0.6	1.2
Tar (%)	0.3	0.4	0.7	1.1
Biomass (%)[a]	0.1	0.3	0.3	0.2
Gas coke (%)	0.1	0.2	0.2	0.2
Other petroleum secondary sources (%)	0.0	0.1	0.3	0.4
Wind power (%)	0.0	0.0	0.0	0.1

[a] Does not include biomass from sugarcane.

It is important to note that the emission coefficient from electricity was estimated according to the set of energy sources summarized in Table 5. The importance of these decompositions of energy sources relates to the fuel components used for electricity generation. Therefore, the estimation of CO_2 emissions also include emissions from electricity.

Data on carbon content, industry activity and carbon oxidations are taken from the values adopted for Brazil according to the national inventory of GHG emissions and values presented by the General Coordination for Global Climate Change of the Brazilian Ministry of Science and Technology (MCT, 2009). Otherwise, emissions default values are taken from IPCC (2006).

GDP data are given in real 2009 US$ and come from the table of energy and social economy aggregated by EPE (2010). Population data were taken from the Brazilian Institute of Geography and Statistics (IBGE, 2010).

Several generalizations and inherent limitations of the decomposition methodology are usually associated with imperfections in defining emissions change. One major generalization is the usage of current values for energy content, conversion rates and emission factors in defining the emission performance of the energy in a time-series analysis.

A second generalization that has a possible, even though marginal, impact on the results is the assumption that renewable energy sources have zero net emissions. While for hydropower and nuclear energy such an assumption is justified easily by the natural characteristics of these energy sources, the assignment of zero emissions coefficients to biofuels and biomass is based on a general assumption of equivalence of emissions from biofuels and biomass combustion and the CO_2 intake along the cultivation stage of these fuels (Macedo et al., 2004; Pacca and Moreira, 2009).

The choice of time interval is also subject to controversy. In general, the selection of intervals is based on policy changes or energy mix transition, with inappropriate intervals leading to loss of accuracy in the analysis (Sun, 1998). In most studies for Brazil, researchers have used five-year intervals; however, several studies also use others intervals with minor changes in the results. The choice for five-year intervals is considered to be consistent with the volatility of the domestic economy, shifts in political structure and changes in the energy matrix of the country after 1970 (Mendonça and Gutierez, 2000; Medeiros and Dezidera, 2006).

4. Empirical evidence and discussion

Discussion on energy consumption related emissions change from 1970 to 2009 and the associated underlying factors are summarized in this section. Fig. 3 presents the contribution of driving factors of emissions change for selected time intervals.

Fig. 3 reveals the diversity of the determinants of CO_2 emissions change. In general, economic activity and population growth are the major determinants of changes in emissions. The importance of economic activity and population growth in determining emissions change has been observed in previous studies on Brazil, notably in Mendonça and Gutierez (2000), Vehmas et al. (2003), Medeiros and Dezidera (2006), Kojima and Bacon (2009) and Vehmas (2009). Therefore, findings of the combined usage of national dataset and LMDI confirm preliminary evaluations carried out on Brazilian case.

A disruption in the combined trend between economic activity and emissions after 2004 with particular emphasis on records for 2009 is worth of specific attention. Estimation of CO_2 emissions from energy consumption in 2009 evidences a reduction of 4.7% compared with 2008, concomitant with an increment of 0.3% in national GDP. This is illustrated in Fig. 4.

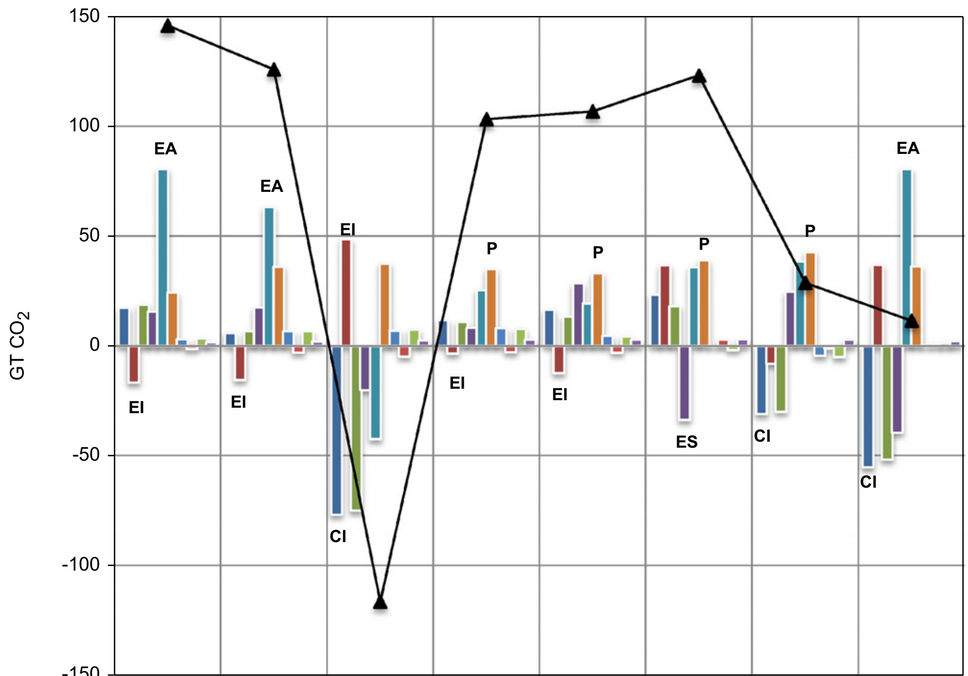
Considering the performance in a time trend, it is verified that the phenomenon that culminated in the observation for 2009 started in 2004 and has precedence in the period between 1980 and 1994. Vehmas et al. (2003) have already noticed the evidence of delinking between economic growth and CO_2 emission for Brazil in the period 1980–1990. Such events are referred by the OECD (2002) as decoupling between emission and economic output. Results for 2008–2009 represent a possible first event of absolute decoupling in Brazil and further exams with special focus on this issue are necessary.

The weight of population growth is also aligned to previous studies and do not show significant change in recent years. Fig. 3 show that the demographic pressure has contributed positively to the increase in carbon emissions in Brazil along the last four decades reflecting the relevance of population growth as an inductor of emissions in the country.

The role of the structure of the economy as a determinant of CO_2 emissions change is associated to the path of development adopted in Brazil in different intervals. The values examined in Fig. 3 for example reflect experiences of multiple reformulation of the economic structure interchanging intervals of growth in energy-intensive sectors and others of fast development of services sectors. A study by Wachsmann et al. (2009) showed that in Brazil structural arranges favoring exporting-oriented industries or infrastructure-related investments, among other sectorial compositions, are potentially associated with higher energy demand, which has an associated impact on emissions.

Regarding energy intensity, it is noticeable that this factor has an unstable pattern with possible relation with economic activity. In other words, during most periods of decline in economic activity, energy intensity increased, and vice-versa. Increases in energy intensity reflect losses of efficiency in the usage of energy and exposes fragilities in policies designed to promote energy savings, improvement in production chain management and continuous technological improvements. Machado and Schaeffer (2006) have already noticed the volatile pattern of energy intensity factor in Brazil interchanging periods of robust growth and other of decrease. Fig. 3 shows a particular interruption in this trend after 1995 when increments in both economic activity and energy intensity fundamentally moved in the same direction.

Observed progresses toward emissions reduction is attributable in most cases to the shifting of the energy mix and the consequent impact on carbon intensity. Fig. 3 evidences robust decrease in carbon intensity in periods after the introduction of renewable sources in the energy matrix. The increments in carbon intensity observed for the period 1990–2000 correspond to the deregulation of the sector and the effect of electricity supply shock that resulted in the extensive usage of thermopower to overcome hydropower



	1970-1974	1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2009
CI	17.2	5.9	(76.9)	11.7	16.6	23.2	(31.1)	(55.4)
EI	(16.7)	(15.6)	48.5	(3.6)	(12.4)	36.6	(8.1)	36.8
EM	18.7	6.6	(75.1)	10.9	13.3	18.0	(30.0)	(51.9)
ES	15.5	17.5	(20.1)	8.2	28.6	(33.8)	24.8	(39.5)
EA	80.4	63.2	(42.5)	25.4	19.4	35.9	38.4	80.5
P	24.3	36.1	37.6	34.8	32.9	39.1	42.7	36.2
CIR	3.0	6.6	7.0	8.0	4.5	0.2	(4.6)	0.3
EIR	(1.5)	(3.0)	(4.9)	(2.9)	(3.1)	2.7	(1.2)	1.0
EMR	3.3	6.6	7.4	7.8	4.3	(1.9)	(5.2)	1.3
PR	1.6	2.0	2.5	2.8	2.8	3.0	2.9	2.2
CO2	145.8	125.8	(116.6)	103.2	106.7	123.1	28.6	11.4

Fig. 3. Decomposition of energy use-induced CO_2 emissions in Brazil by determinant (1970–2009).

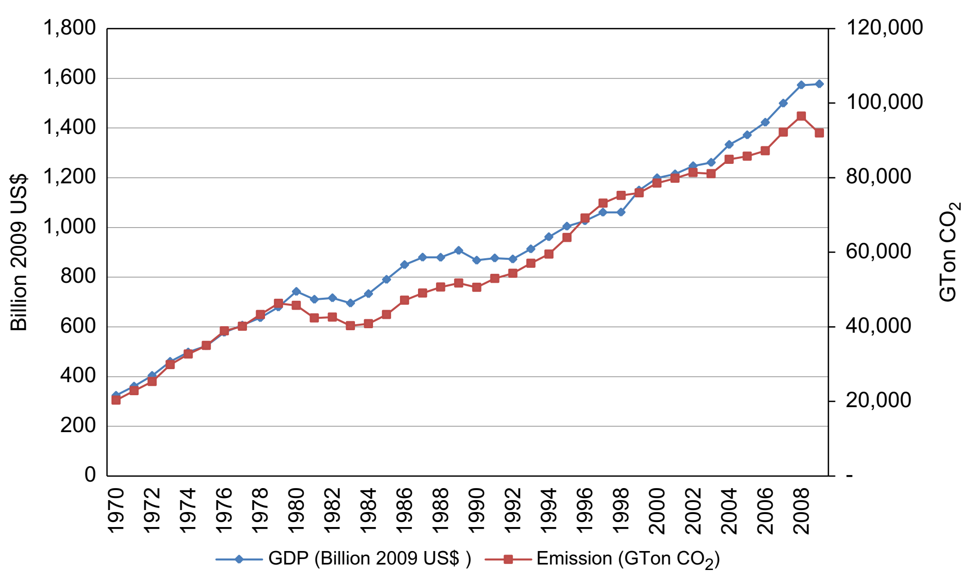


Fig. 4. CO_2 emissions from energy consumption and GDP in Brazil (1970–2009).

supply deficits (La Rovere, 2002; Anuatti-Neto and Hochstetler, 2002).

In all intervals it is observed a secondary importance of residential factors to aggregate emissions change in the country. Regardless of the magnitude of the emissions from households, already observed by Wachsmann et al. (2009), it is noteworthy that evolution of the underlying factors in this sector follows in large degree a distinctive pattern compared to observation for the aggregate of productive sectors. It is remarkable from the results the relevance of energy intensity improvement as an important factor for emission mitigation from household reflecting the adaptation of consumers to policies and increases in energy price registered in the period (EPE, 2010). Population effect has a leading weight in pushing emissions growth in residential sector in the last 15 years. Such observation complements previous study addressing emissions from residential sector, notably that by Achão and Schaeffer (2009) who did not include energy mix variable in their analysis. Finally, reduced levels of emissions from the household are in large degree associated to the lower carbon content of energy consumed in the sector.

5. Conclusions

This study assesses the changes in CO_2 emissions from energy consumption in Brazil. The results show that emissions change has been predominantly influenced by economic activity and population growth. It was observed that fuel diversification toward lower emissions sources and carbon intensity are amongst the factors that contributed to the deceleration of emissions growth for the period 1970–2009. Energy intensity presents a volatile weight interchanging intervals of growth and reduction along the assessed four decades. A similar pattern is observed for economy structure factor reflecting the historical development of the economy.

The study provides an updated evaluation of emissions change in Brazil combining official energy data for Brazil and LMDI decomposition method. Also, it is evaluated for the first time the recently released data for energy balance with records for 2009. Emissions are estimated for all sectors and energy sources consumed in the country including emissions from the share of nonrenewable sources used to electricity generation.

Results confirm most of preliminary findings reported in the literature and offer complementary perspective on several uncovered issues. Furthermore, it presents evidences of a possible occurrence of absolute decoupling between economic growth and CO_2 emissions from energy consumption in Brazil in 2009. The observation for 2009 follows events of relative decoupling starting in 2004 and represents a positive answer of policy towards energy mix diversification and other concerns on environmental issues.

The diversification of energy mix toward lower emissions sources confirms the benefits of a relatively clean energy matrix in Brazil and evidences a positive performance of efforts carried out by public authorities along the last 10 years. Among the renewable energy sources, the energy derivatives of sugarcane, i.e. ethanol fuel and cogenerated electricity, experienced the higher growth rate during the evaluated period being the possible main beneficiaries the industrial, energy generation and transport sectors. Furthermore, the trend in aggregate CO_2 emissions suggests that economic activity, population growth and unstable pattern of energy intensity have partially offset the most of the expected benefits of carbon intensity reduction and an improved fuel mix in the last four decades.

Finally, the results suggest that emissions from energy consumption in Brazil are an issue of major concern. Findings indicate that efforts beyond the maintenance of the energy matrix diversification policy are apparently neglected and confirm some of the concerns raised by critics of Brazilian proposals toward emissions reduction. The results of this study indicate that additional attention to the decoupling of economic activity and emissions, progressive reduction of energy intensity and the development of low emissions sectors could contribute positively to reduced emissions from energy consumption in the country. Further evaluations on sectorial level are strongly encouraged in order to identify sectorial contribution to emission change.

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