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Research paper

Domestic versus foreign origin of total energy use: An analysis for Brazil

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ABSTRACT

Energy use is the major source of greenhouse gas emissions. The aim of this paper is to examine total domestic and foreign energy use across industries in Brazil over the period 1995–2015. We found that total energy use experienced an annual average growth rate close to 3%. In 2015 only three industries accounted for 37% of total energy use in Brazil: Transport, Food & Beverages, and Electricity, Gas, and Water. In these industries the share of the energy used and produced domestically was higher than the average (85.6%, 84.5% and 94.5% of the total, respectively). In contrast, other industries were increasingly reliant on foreign energy. Thus, the share of domestic use of energy produced abroad was higher than 20% in Textiles and Wearing Apparel, Electrical and Machinery, Transport Equipment and Construction. This fact extends the problem of energy-related emissions mitigation from the national to the global level.

1. Introduction

To reverse the current climate situation, we need to change our energy use patterns. Governments around the world have issued plans to transition to more sustainable energy systems able to reduce energy-related carbon dioxide and other greenhouse gas (GHG) emissions. Over the last years, the number of studies that examine trends in energy use and emissions rose substantially (Aydin, 2014a,b, 2015a,b; Aydin et al., 2012; Azadeh and Tarverdian, 2007; Feng and Zhang, 2012; Harun et al., 2021; Hastuti et al., 2021; Köne and Büke, 2010; Su et al., 2019; Su and Ang, 2020; Wan et al., 2021; Wang et al., 2021; Wang and Yang, 2020; Wang and Zhou, 2019; Zhu et al., 2020). They conclude that to mitigate climate change it is necessary to phasing out fossil fuels and stimulate renewable energy deployment, especially in industry and transport sectors, where renewables still meet low shares of their total energy use. According to the IEA World Energy Outlook 2019, energy-related emissions hit an historic high in 2018 as global energy demand increased at almost twice the average rate of the decade (IEA, 2019). However, because of the COVID-19 pandemic, in 2020 world primary energy consumption experienced the largest decline since 1945 and emissions fell by 6.3%. This decline was mainly explained by the drop in oil consumption. In spite of this drop, in 2021 oil still accounted for the largest share in the world energy mix (31.2%), followed by coal (27.2%), natural gas (24.70%), hydroelectricity (6.9%), renewables (5.7%) and nuclear energy (4.3%) (BP, 2021). Nonetheless, as the IEA Executive Director Fatih Birol points out, "low economic growth is not a low-emissions strategy". In other words, it is necessary to introduce structural changes both in production and consumption if we want to substantially reduce GHG emissions (IEA, 2020c).

Over the last decades Brazil has undergone radical changes in its economic, social, and environmental structure (Marconi et al., 2016; Wachsmann et al., 2009) and it is one of the main developed economies in the world (IBGE, 2020; IPEA, 2020). Among the major changes experienced by the country we can highlight its increase in industrial activity and exports and the subsequent rise in industrial energy use (Banday and Aneja, 2020; Bhat, 2018; Kim and Tromp, 2021; Montoya et al., 2021). Thus, despite over the period 2014–2019 there was an annual decline in industrial GDP per capita of 3.9%, industrial energy intensity grew at an annual average rate of 1.3%. The major reason was the rise in the share of energy-intensive industries (Ministério de Minas e Energia, 2020b). Nowadays, Brazil is the eight largest total energy supplier in the world. It also the eight largest producer and consumer of electricity (IEA, 2020a). Despite more than 80% of total electricity supply is generated by renewables, 54% of the energy consumption of the country is still based on fossil energy. Oil and its products show the largest share in the energy mix

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(34%), followed by natural gas (12%) and coal (5%). Among renewables, sugarcane biomass is the major source (18%), followed by hydropower (12.4%) and firewood and charcoal (8.7%) (Ministério de Minas e Energia, 2020b). From a sectoral perspective, in 2019 transport and industrial consumption accounted for more than 63% of the total energy consumption of the country. In contrast, household consumption only represented 10.3% of total energy consumption (Ministério de Minas e Energia, 2020a). It is necessary to note that there is a high heterogeneity in energy intensity across industries. Thus, if we compare the shares in final energy consumption across industries, we can highlight that only three industries, namely, steel, sugar, and pulp and paper, accounted from more than half of industrial final energy consumption. In terms of energy intensity, the most energy-intensive industry was paper and pulp (Ministério de Minas e Energia, 2020a).

The Paris Agreement is the first ever legally binding global climate change agreement. In compliance with Article 4, paragraph 12 of the Paris Agreement, countries must communicate their Nationally Determined Contributions (NDCs) to reduce their GHG emissions. The ambitious Brazilian NDC was reformulated in 2020. A target to reduce GHG emissions by 37% and by 43% in 2030 compared to 2005 levels was set. The achievement of this target is mainly based on increasing the share of "other renewables", like solar photovoltaic energy, wind energy and biofuels (Lima et al., 2020; Pereira et al., 2012), as hydropower is highly dependent on the hydrological cycle (Mendes and Sthel, 2017). Gurgel et al. (2019) highlight, the use of fossil energy is one of the main explanatory factors for GHG emissions in Brazil, in combination with agriculture and land-use changes and deforestation. Table 1 provides an overview of different measures proposed to reduce energy-related emissions in Brazil.

As can be seen, most of the proposed measures focus on reducing the impact of high energy-intensive industries and on rising the share of low carbon industries. An essential previous step to introduce most of these measures is the identification of the most energy-intensive industries within the production system. The aim of this paper is to examine the evolution of total (both direct and indirect) energy use across the Brazilian production system over the period 1995–2015. For doing so we employ an extended multi-region input output (MRIO) model. As Lenzen et al. (2013) point out, MRIO-based studies can be particularly useful to bring the issue of energy (and carbon) embodied in international trade to wider audiences. Compared to other methodological approaches that are conducted at the micro-level and adopt a bottom-up perspective (like life-cycle assessment), MRIO models employ a top-down approach and are carried out at the macro-level. According to Chen et al. (2020) this allows to trace total energy flows across industries and across countries and to capture the impact of globalization on energy use. Moreover, compared to the analysis of direct energy use, MRIO models provide a more systematic perspective of energy use (Chen and Chen, 2011; Chen and Wu, 2017) and allow "to discover where the real energy use occurs in the production chains" (Wachsmann et al., 2009, p. 586). It is necessary to note, however, that these models also have drawbacks. These are mainly related to the time lag in the publication of MRIO tables and the hypotheses on homogeneity, proportionality and imports that are assumed (Miller and Blair, 2009).

To the best of our knowledge, there is no study that estimates total energy use at the industry level differentiating between the domestic and foreign origin of the energy used in Brazil. The results of our analysis reveal the existence of different energy use patterns among the Brazilian industries. Thus, for one part, we find high energy-intensive industries that rely mainly on energy produced in the country. For the other part, there are some industries increasingly reliant on energy produced abroad. These results can be useful for national energy policy making. They can serve as a basis for domestic energy use regulation and for adjustments in the international trade structure. Given the close relationship between energy use and GHC emissions, these results can also help to better design measures aimed at reducing energy-related emissions.

The remainder of the paper is organized as follows. First, we briefly review the literature dealing with energy use, paying special attention to those studies that focus on Brazil. Second, we present the data and methodology employed. Next, we comment on the results obtained. Finally, we summarize the main conclusions reached and elaborate some policy recommendations.

2. Energy use in Brazil: a review of the literature

Due to the close relationship between energy and GHG emissions, a high number of studies dealing with energy use have emerged over the last decades. We can trace back the interest in embodied energy flows to the energy crisis of the 1970s (Binder, 1974). Thus, in 1973 Robert Herendeen (Herendeen, 1973) introduced the concept of embodied energy drawing on the physiocratic theory (Quesnay, 1758). The basic idea was that primary energy enters into society and circulate in the form of embodied energy in the different goods and services. So, to get an accurate estimation of total energy use, it is necessary to take into account that embodied energy flows (Bullard and Herendeen, 1975a,b; Hannon, 2010; Herendeen, 1978, 2004). These models were based on traditional input–output analysis (IOA) (Leontief, 1936) although in some cases they were combined with life cycle analysis (LCA) giving place to hybrid models (Bullard et al., 1978). In the late 1970s and early 1980s decomposition analyses (DA) were developed to examine energy efficiency at the industry level. According Hoekstra and van den Bergh (2003), there are two main types of DA: structural decomposition analysis (SDA) and index decomposition analysis (IDA). While SDA uses input output data IDA does not employ any input output model. IDA can be linked to two main groups of methods: the first one is based on the Laspeyres index and the second one draws on the Divisia index (Ang, 2004).

The new oil crisis that caused the explosion of oil prices in the 1990s brought about a renewed interest in energy flows, and more concretely in embodied energy flows (Adelman, 1990). More recently, the focus has moved to the environmental impact or energy footprint. Different approaches can be distinguished when analyzing embodied energy flows. The best known is IOA, which has been widely used both at local and global scales (Chen et al., 2020). Two other methods are LCA, which is commonly used to evaluate specific products or technologies (Goldstein et al., 2013; Lee and Tzeng, 2008; Nabavi-Pelesaraei et al., 2017; Pehnt, 2006), and ecological network analysis (ENA), which is employed to assess the sustainability of energy systems (Kharrazi et al., 2014; Zhang et al., 2010). Among the most recent studies on energy modeling we can highlight those conducted for agricultural sector (Ghasemi-Mobtaker et al., 2020; Khanali et al., 2021; Mostashari-Rad et al., 2021; Nabavi-Pelesaraei et al., 2021a,b).

Within IOA, MRIO models estimate the energy use and GHG emissions occurring along global supply chain (Chen et al., 2018, 2019, 2020; Chen and Chen, 2011, 2013; Chen and Wu, 2017; Gyamfi et al., 2021; Shepard and Pratson, 2020; Wu et al., 2019a,b, 2020; Wu and Chen, 2017; Zhang et al., 2019; Zhao and Liu, 2020). In a context of increasing inter-dependencies of countries, it is essential to take into account that a growing share of the total energy use of a country is composed of the energy use induced by goods and services produced abroad. Many papers on energy footprint include Brazil within the groups of countries analyzed. We can cite as examples the study by Lan et al. (2016)

Table 1
Overview of measures proposed to reduce energy-related emissions in Brazil.
Source: Own elaboration

Authors	Measures
Bastidas and Mc Isaac (2019)	Shifting final demand from fossil energy-intensive industries like food and vehicles to service industries like tourism and health and education
Carvalho et al. (2020)	Introduction of low carbon energy technologies, development of the bioenergy market and the strengthening of low carbon energy industries
Chen et al. (2013)	Adjusting the industrial structure by reducing both energy-intensive producing industries (like coal and mining or petroleum refinery) and energy-intensive user industries (like non-metallic products, metals, or machinery)
Kim and Tromp (2021)	Shifting production and consumption to cleaner products by using carbon taxes and carbon tariffs.
Köberle et al. (2020)	Introduction of low-carbon sources for all energy carriers, switching from fuel in transportation, fostering energy efficiency in industry and transportation and promoting low-carbon power generation like biomass, wind, and solar
Lampreia et al. (2011)	R&D investments and technological learning
Lefèvre et al. (2018)	Introduction of a subsidy for pre-salt oil domestic refining and consumption
Lucena et al. (2016)	Improvement of professional qualifications in renewable energy
Teixeira M.D. de et al. (2020)	Targeting investments in strategic sectors like the forest sector, agriculture, transportation, and some industrial sectors

Table 2
Studies on energy use in Brazil.
Source: Own elaboration.

Authors	Period	Method	Sector
Schaeffer and de Sá (1996)	1970–1993	IOA	Industries
Machado and Schaeffer (1997)	1995–2015	IOA	Industries
Machado et al. (2001)	1990–1998	IOA	Industries
Tolmasquim and Machado (2003)	1995–1996	IOA	Industries
Montoya et al. (2014)	2009	IOA	Industries
Arbex and Perobelli (2010)	2009	IOA + other	Industries
Carvalho et al. (2015)	2009	IOA + other	Industries
Carvalho et al. (2016)	2009	IOA + other	Industries
Cohen et al. (2005)	1995	DA	Households
Achão and Schaeffer (2009)	1980–2007	DA	Households
Sanches-Pereira et al. (2016)	2009	DA	Households
Abrahão and Souza (2021)	2000–2018	DA	Households
Wachsmann et al. (2009)	1990–2010	DA	Industries and households
de Freitas and Kaneko (2011)	1970–2009	DA	Industries and households
Montoya et al. (2021)	2015	IOA	Industries and households

for 186 countries, by Chen et al. (2019) for 40 countries, by Zhang et al. (2019) for the BRICS group or by Gyamfi et al. (2021) for the emerging industrialized seven (E7) economies. However, the number of studies that focus on Brazil is scarcer. They are summarized in Table 2. For one part, we can find studies that examine energy use starting from IOA at the industry level (Arbex and Perobelli, 2010; Carvalho et al., 2015, 2016; Machado et al., 2001; Machado and Schaeffer, 1997; Tolmasquim and Machado, 2003) and, for the other part, studies that employ DA at the household level (Abrahão and Souza, 2021; Achão and Schaeffer, 2009; Cohen et al., 2005; Sanches-Pereira et al., 2016). Some studies take into consideration both perspectives (de Freitas and Kaneko, 2011; Wachsmann et al., 2009).

At the industry level, the paper by Schaeffer and de Sá (1996) estimates the fossil energy associated with the production of Brazilian merchandise exports and imports for the period 1970–1993 by combining international trade data and energy intensities from input–output tables. This energy was converted to carbon emissions by using the carbon content of fuel oil. The results obtained show that while Brazil was a net energy importer over the period 1970–1979, it turned into a substantial net energy exporter between 1980–1993. The study by Machado and Schaeffer (1997) estimates the evolution of energy embodied in Brazilian industrial exports over the period 1995–2015 under different scenarios. They conclude that there is a tradeoff between the effectiveness of those measures aimed at improving an efficient energy use and the growth of the exports of energy-intensive goods. Machado et al. (2001) employ IOA in hybrid units to assess the impact on total energy embodied in Brazilian exports on CO_2 emissions in 1995. They highlight that Brazil is not only a net exporter of embodied energy but also that each dollar earned with exports embodied more energy and more carbon than each dollar spent on imports. In a complementary way, the analysis of energy and carbon embodied in Brazilian international trade conducted by Tolmasquim and Machado (2003) reveals that the energy and CO_2 embodied in Brazilian exports are concentrated in some energy-intensive industries like pulp and paper, iron and steel, non-ferrous metals, non-metal minerals, chemicals, mining and quarrying products and food and beverages. Montoya et al. (2014) constructed an input–output model in hybrid units starting from the 2008 input–output matrix of Brazil. Arbex and Perobelli (2010) combine IOA with a growth model to simulate energy consumption in eleven industries in Brazil. In a similar way, Carvalho et al. (2015, 2016) combine IOA with multi-objective models to analyze the tradeoffs between the maximization of production and employment and the minimization of energy consumption and emissions in Brazil. An inverse relationship between these two objectives is found.

Rather than on industries, some studies put the emphasis on the energy use of households. Thus, Cohen et al. (2005) examine total energy requirements of Brazilian households in 1995–1996. As expected, they point out the existence of a positive relationship between energy use and income level. However, compared to other countries, mobility accounts for larger share of total energy requirements. Achão and Schaeffer (2009) analyze the evolution of residential electricity consumption by Brazilian households over the period 1980–2007, highlighting the importance of social programs to reduce regional disparities. In this sense, we can note that in a comparative study of Australia, Brazil, Denmark, India and Japan, Lenzen et al. (2006) employ multivariate analysis to examine the importance of socio-demographic characteristics on household energy requirements. They find three key explanatory variables for energy requirements in Brazil, namely, expenditure, education and household size. Sanches-Pereira et al.

(2016) examine the evolution of Brazilian residential energy consumption and its impact on emissions over the period 2000–2013, underlying again the importance of regional disparities. More recently, Abrahão and Souza (2021) analyze the drivers of Brazil's residential electricity consumption. They conclude that income does not have a clear impact on consumption in hot climate regions and that consumption decreases with age.

Wachsmann et al. (2009) examine changes in energy use of Brazilian industries and households over the period 1970–1996 using SDA. They conclude that changes in energy use in Brazil were mainly driven by changes in affluence, the number of people and intersectoral dependencies. de Freitas and Kaneko (2011) go beyond energy use, and by applying SDA, estimate the impact of energy consumption on emissions in Brazil over the period 1970–2009. They find that economic activity and demographic growth are the main drivers of emissions and that households play a minor role compared to industries. More recently, Montoya et al. (2021) examine the impact on emissions of renewable and non-renewable energy embodied in international trade. Their results show that Brazilian exports contribute to reduce world emissions as 39.4% of emissions embodied in exports have their origin in renewable energy.

None of the studies mentioned above differentiate between the domestic and foreign origin of the energy used at the industry level. To trace total energy use of a specific industry it is necessary to include the energy embodied in intermediate inputs. In addition, it is important to distinguish whether the energy used is produced in the own country or in the rest of the world. In the following section we describe the data and the methodology employed.

3. Data and methodology

3.1. Data

Nowadays, various MRIO databases are available with different regional and sectoral classifications, such as the Eora database (Lenzen et al., 2012, 2013), the World Input–Output Database (WIOD) (Timmer et al., 2015, 2016), the Global Trade Analysis Program (GTAP) database (Aguiar et al., 2019), EXIOBASE (Stadler et al., 2018; Wood et al., 2018) which is a product of the EXIOPOL project (Tukker et al., 2013), and the Organization for Economic Co-operation and Development Inter-Country Input–Output (OECD ICIO) database, which is based on the United Nations Uniform of the International Standard Industrial Classification of All Economic Activities (ISIC) (OECD, 2018). In this paper we employ the Eora database, and more concretely its version 1998.82, that include a high number of countries (189) and has a sectoral coverage of 26 sectors (Eora, 2019). In difference with other databases, Eora's guiding principle is to avoid transformations of the original raw data as much as possible for the sake of transparency (Lenzen et al., 2013). Concerning energy data, energy flows were expressed in Terajoules (TJ) by using energy data from the IEA (IEA, 2020a).

3.2. Methodology

The IO model for a single country was introduced by Leontief in 1936 (Leontief, 1936) and environmentally extended in the 1970s (Leontief, 1970). In this model the total output required by country r to satisfy a certain final demand is expressed as follows:

$$x^r = A^r x^r + y^r, \tag{1}$$

where x^r is a vector of sectoral outputs in country r; A^r is a matrix of intermediate consumptions representing the industry requirements to produce one unit of output; and y^r is the final demand vector in country r.

Since imports are usually required to produce exports, direct energy use does not reflect the total energy use. In order to estimate total energy use, it is necessary to incorporate the energy used to produce exports. Thus, as an extension of the economic MRIO table, an energy use MRIO table can be built starting from the monetary flows and the energy resources of Brazil aggregated into n countries and k sectors. Table 3 shows the structure of the energy use MRIO table.

The energy use MRIO table is composed of five major blocks: the intermediate uses block, the final demand block, the value-added block, the output block, and the energy use block. Output can be obtained by adding intermediate uses and final demand or by adding intermediate uses and value added. All these blocks can be written in matrix or vector form.

In the intermediate uses matrix, Z^{sr}, each element z_{ij}^{sr} shows the intermediate uses from industry i in country s to industry j in country r. In the final demand matrix, Y^{sr}, each element y_i^{sr} represents the final goods from industry i in country s to satisfy the final demand in country r. In the value-added vector, υ^s, each element υ_j^s shows the value added generated in industry j in country s. The output vector, x^s, each element x_j^s shows the output of industry j in country s. Finally, in the energy use vector, e^s, each element e_j^s shows the energy use of industry j in country s.

We can construct an intermediate consumption matrix A^{sr} by dividing the intermediate uses matrix Z^{sr} by a diagonalized output vector $\hat{x}^r$ as follows:

$$A^{sr} = Z^{sr} \left(\hat{x}^r\right)^{-1}. \tag{2}$$

Each element a_{ij}^{sr} of the matrix A^{sr} shows the intermediate inputs from industry i in country s necessary to produce one unit of output in industry j in country r.

Starting from Eq. (1), the standard IO model can be written as follows:

$$x^s = \sum_{r=1}^{n} A^{sr} x^r + \sum_{r=1}^{n} y^{sr} \tag{3}$$

where x^s is a vector of sectoral outputs in economy s; A^{sr} is a matrix of intermediate consumptions; and y^{sr} is the final demand vector from economy s to r.

Rearranging Eq. (3), we obtain the following expression:

$$x^s = \sum_{t=1}^{n} B^{st} y^{tr}, \tag{4}$$

where $\mathrm{B} \equiv (\mathrm{I} - \mathrm{A})^{-1}$ is the Leontief inverse matrix. Matrix B^{st} shows the amount of output in a producing country s required for a one-unit increase in the final demand in destination country r.

To estimate the total (direct plus indirect) energy use, we need to construct the energy use vector e^s in the same manner as we constructed the intermediate consumptions matrix:

$$\left(e^s\right)' = \left(\varepsilon^s\right)' \left(\hat{x}\right)^{-1}. \tag{5}$$

where ε^s is a vector of direct energy use in country s. Each element e_j^s of vector e^s shows the direct energy use per unit of output in industry j of country s.

The total energy use (E^{sr}) of country s from country r can be obtained by pre-multiplying Eq. (4) by the direct energy consumption vector as follows:

$$E^{sr} = \sum_{t=1}^{n} \left(e^s\right)' B^{st} y^{tr}. \tag{6}$$

The Leontief inverse matrix B can be decomposed into two matrices: B^d, which represents the domestic sectoral relationships, and

Table 3
Structure of the energy use MRIO table.
Source: Own elaboration.

Input			*Output*										
			Intermediate uses							Final demand			*Output*
			Country 1			…	Country n			Country 1	…	Country n	
			Industry 1	…	Industry k	…	Industry 1	…	Industry k	H …	…	H …	
Intermediate inputs	Country 1	Industry 1	z_{11}^{11}	…	z_{1k}^{11}	…	z_{11}^{1n}	…	z_{1k}^{1n}	y_1^{11}	…	y_1^{1n}	x_1^1
		…	…	…	…	…	…	…	…	…	…	…	…
		Industry k	z_{k1}^{11}	…	z_{kk}^{11}	…	z_{k1}^{1n}	…	z_{kk}^{1n}	y_k^{11}	…	y_k^{1n}	x_k^1
	…	…	…	…	…	$\boldsymbol{z_{ij}^{sr}}$	…	…	…	…	$\boldsymbol{y_i^{sr}}$	…	x_i^s
	Country n	Industry 1	z_{11}^{n1}	…	z_{1k}^{n1}	…	z_{11}^{nn}	…	z_{1k}^{nn}	y_1^{n1}	…	y_1^{nn}	x_1^n
		…	…	…	…	…	…	…	…	…	…	…	…
		Industry k	z_{k1}^{n1}	…	z_{kk}^{n1}	…	z_{k1}^{nn}	…	z_{kk}^{nn}	y_k^{n1}	…	y_k^{nn}	x_k^n
Value added			v_1^1	…	v_k^1	$\boldsymbol{v_j^s}$	v_1^n	…	v_k^n				
Output			x_1^1	…	x_k^1	$\boldsymbol{x_j^s}$	x_1^n	…	x_k^n				
Energy use			e_1^1	…	e_k^1	$\boldsymbol{e_j^s}$	e_1^n	…	e_k^n				

B^a which accounts for the sectoral relationships with the rest of the world.

$$B = B^d + B^a \tag{7}$$

The final demand Y can also be decomposed into two matrices: Y^d, which represents the domestic final demand, and Y^f which represents the final demand from the rest of the world.

$$Y = Y^d + Y^f \tag{8}$$

Using these two decompositions, we can rewrite Eq. (6) as follows:

$$E_{0j}^{sr} = e_{0j}^{0s} \cdot B_{ij}^{sr} \cdot Y_{i0}^{sr}. \tag{9}$$

If we use the decomposition of energy use associated to final demand, we obtain the following expression:

$$E_i^d = E_{i0}^{dd} + E_{i0}^{da} + E_{i0}^{fd} + E_{i0}^{fa} \tag{10}$$

The first term E_{i0}^{dd} shows the domestic use of energy produced domestically. The second term represents E_{i0}^{da} the domestic use of energy produced abroad. The third term E_{i0}^{fd} captures the foreign use of energy produced domestically. Finally, the fourth term E_{i0}^{fa} comprises the foreign use of energy produced abroad. In our case, each of the four terms of Eq. (10) can described as follows:

Firstly, the total energy used and produced in Brazil:

$$E^{dd} = \sum_{j=1}^{n} (e_j.B_{ij}^d.Y_i^d) \tag{11}$$

Secondly, the total energy used in Brazil but produced abroad:

$$E^{da} = \sum_{j=1}^{n} (e_j.B_{ij}^a.Y_i^d) \tag{12}$$

Thirdly, the total energy used abroad but produced in Brazil:

$$E^{fd} = \sum_{j=1}^{n} \left(e_j.B_{ij}^d.Y_i^f\right) \tag{13}$$

Finally, the total energy used and produced abroad:

$$E^{fa} = \sum_{j=1}^{n} (e_j.B_{ij}^a.Y_i^f) \tag{14}$$

The methodology described is summarized in Table 4.

4. Results and discussion

Once described the methodology employed, as a preliminary step before entering into the analysis of total energy use, we examine the evolution experienced by energy production, energy exports and energy imports in Brazil over the period 1995–2019 (IEA, 2020b). Fig. 1 also shows the apparent energy consumption, that is, the sum of energy production plus energy imports minus energy exports (Deardorff, 2014).

As can be noticed, energy production increased substantially over the period 1995–2019. On average, it grew at annual rate higher than 4%. The increase in energy imports was much more modest. On average, energy imports grew at annual rate of 1.2%. In contrast, the pace of growth of exports was much higher: 17.6%. These figures confirm the ascending role of Brazil as net energy exporter as well as its growing self-sufficiency in energy use terms: apparent energy consumption was lower than energy production in the last two years.

The trends shown by exports and imports can be explained by the increases or reductions in the international trade of certain energy sources. For instance, Brazilian energy imports are mainly composed of fossil sources and imports of some of these sources, like crude, NGL and feedstocks, experienced a severe drop between 1995 and 2019.

After describing the recent changes in energy production, exports, and imports, we focus on the changes experienced by total energy use in Brazil. Conventional analyses on energy use focus on the direct energy use by industries. Fig. 2 shows the evolution of total energy use between 1995 and 2015, distinguishing between direct energy use and indirect energy use.

Overall, total energy use experienced a substantial growth over the period examined: it increased at annual average rate close to 3%. As expected, most of total energy use was indirect. In addition, the annual average growth rate of indirect energy use was slightly higher than the rate of direct energy use (3% compared to 2.7%). As a result, the changes in the contribution of direct and indirect use to total energy use were very low: only one percentage point. Thus, while in 1995 direct energy use accounted for 27% of total energy use and indirect energy use for 73%, the participations in 2015 were 26% and 74%, respectively. According to Wachsmann et al. (2009), the importance of Brazil's indirect energy use can be explained, among other factors, by the increasing complexity of production processes, the rise of mechanization and the development of global value chains.

Entering into the domestic or foreign origin of total energy use, Fig. 3 reports the evolution of total energy use in Brazil distinguishing between the four components described above: total energy used and produced in Brazil (DU-PD), total energy used in Brazil but produced abroad (DU-PA), total energy used abroad but produced in Brazil (FU-PD) and total energy used and produced abroad (FU-PA).

Table 4
Schematic table of the methodology.
Source: Own elaboration.

Direct energy use (e vector)	Total intermediate use of inputs (B matrix)	Domestic (B^d) Rest of the world (B^a)	By multiplying the different B and Y matrices by the e vector we obtain the total energy use (E) which can be decomposed into four terms $E = E^{dd} + E^{da} + E^{fd} + E^{fa}$ where: Energy used and produced in the country (E^{dd}) Energy used in the country but produced abroad (E^{da}) Energy produced in the country but used abroad (E^{fd}) Energy used and produced abroad (E^{fa})
	Final demand (Y matrix)	Domestic (Y^d) Rest of the world (Y^f)	

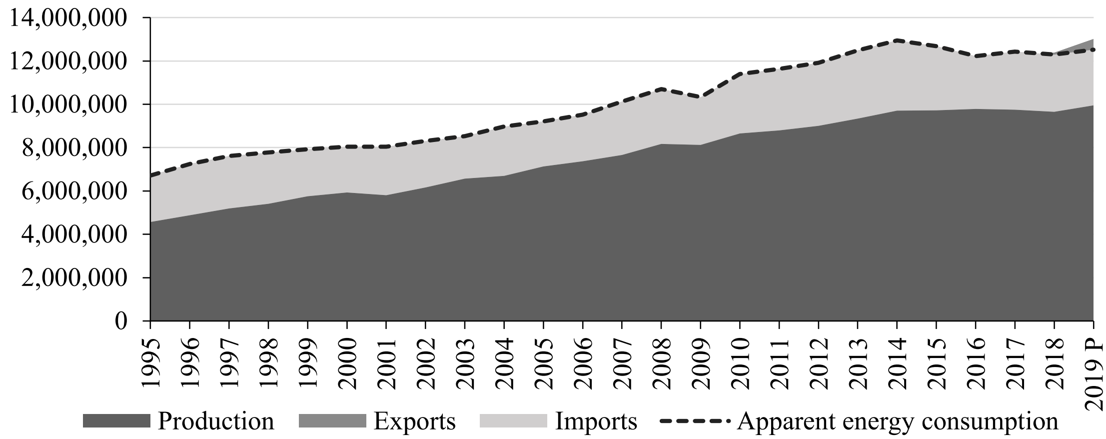

Fig. 1. Evolution of production, exports, and imports of energy in Brazil, 1995–2019.

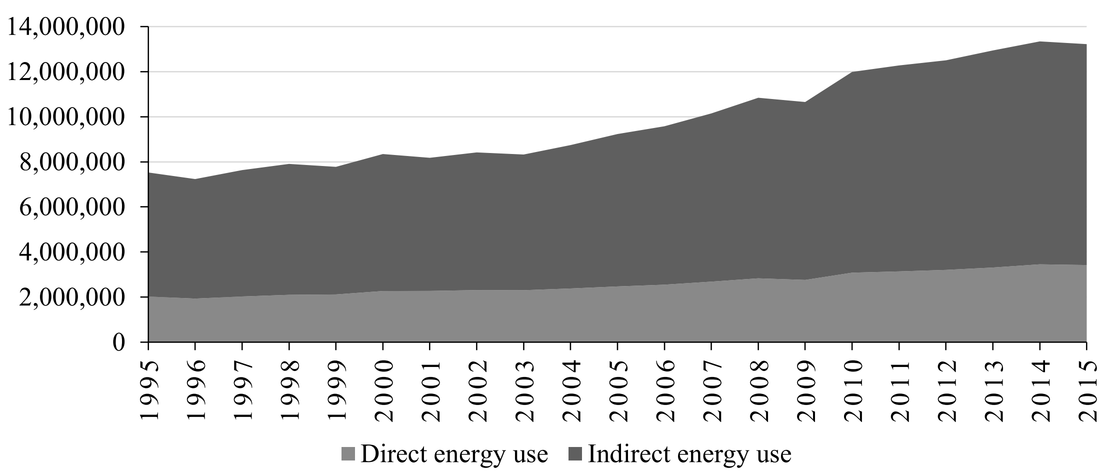

Fig. 2. Evolution of total energy use in Brazil, 1995–2019.

As can be noticed, most of total energy is used in Brazil. However, over the period analyzed, the share of energy used abroad grew substantially, from 3.7% in 1995 to 6.1% in 2015. This increase in the share of foreign energy use was explained by the faster pace of growth of foreign energy use compared to domestic energy use. Thus, while domestic energy use grew at annual average rate of 2.8%, the average annual growth rate of foreign energy use was more than double, 6%.

Concerning to the origin of the total energy used, that is, whether it is produced in the country or abroad, we have to note that, while the share of the energy used in Brazil but produced abroad remained quite stable over the period, there was a substantial increase in the share of the energy produced in Brazil but used abroad (that grew from 3.2% of the total energy use in 1995 to 5% in 2015). In contrast, the share of the energy used and produced in Brazil diminished from 83.3% in 1995 to 80.6% in 2015. In their recent analysis of the largest 136 economies over the period 2000–2015, Shepard and Pratson (2020) find that, on average, 23% of world trade in embodied energy in place between countries that do not have apparent energy trade. This reflects a growing dependence on foreign energy systems that have some benefits in terms of security, as energy disruptions in one specific supply chain will have a low impact on the economy.

Turning to analysis of total energy use at the industry level, Fig. 4 shows the shares of the four components of total energy use (DU-PD, DU-PA, FU-PD and FU-PA) by industry in 1995, 2002, 2008 and 2015. The list of industries is reported in Appendix.

As can be seen, the three greatest energy user industries were 19 Transport, 4 Food & Beverages, and 13 Electricity, Gas, and Water. These three industries accounted for 37% of total energy use in Brazil in 2015. In addition, we have to note that, over the years examined, their share in total energy use remained stable. In contrast, the fourth highest energy user industry, 7

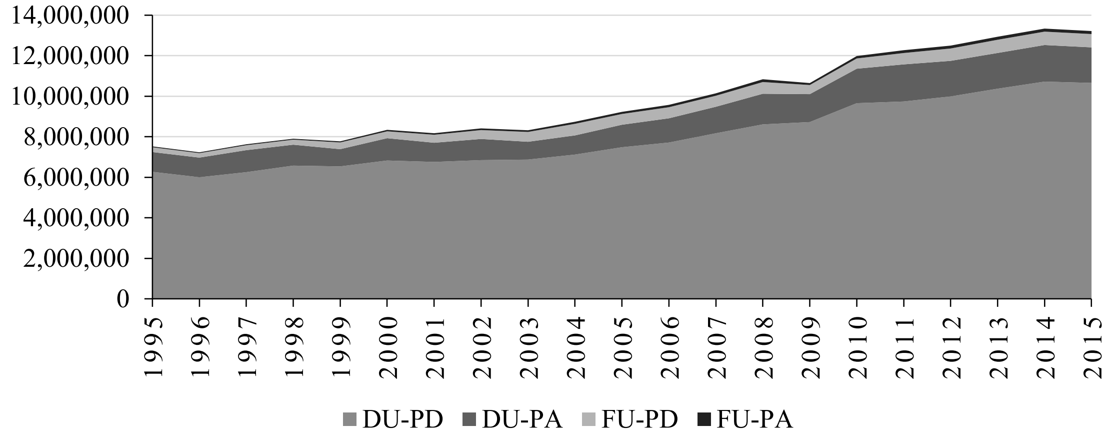

Fig. 3. Evolution of domestic and foreign energy use in Brazil, 1995–2015.

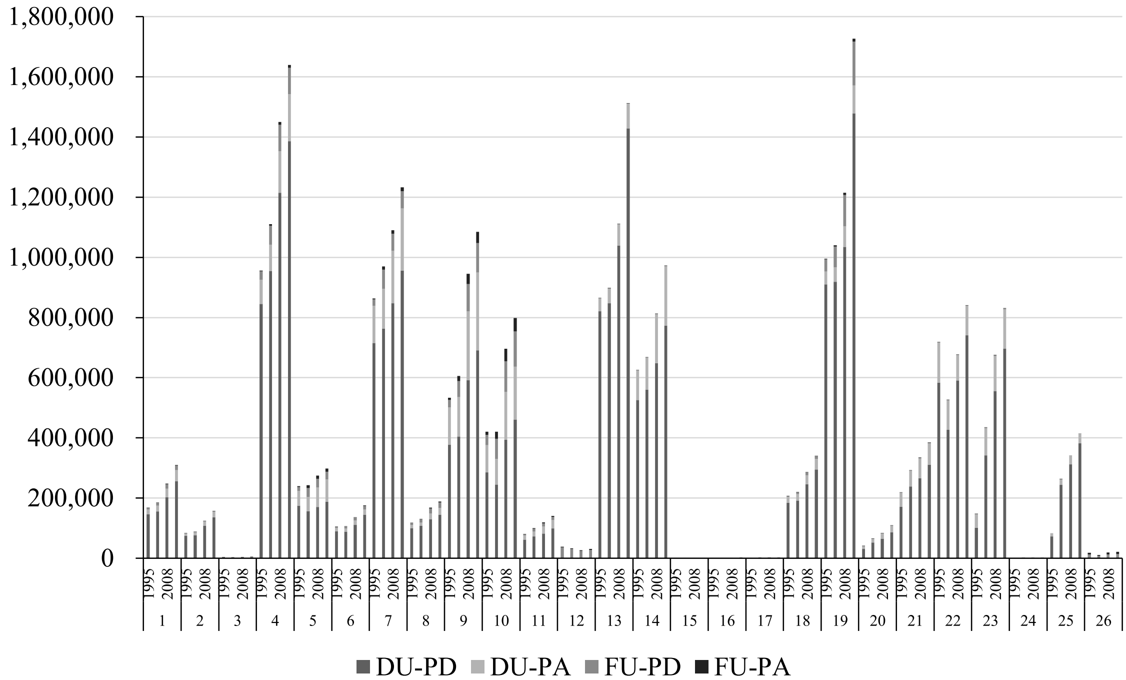

Fig. 4. Evolution of domestic and foreign energy use by industry in Brazil, 1995–2015.

Petroleum, Chemical, and Non-Metallic Mineral Products, diminished its share in total energy use from 11.5% in 1995 to 9.3% in 2015.

At the opposite end of the scale, we find three industries from the service sector: 15 Maintenance and Repair, 16 Wholesale Trade, and 17 Retail Trade. We have to note, however, the existence of very different patterns among the service industries. Thus, both the greatest increase and the greatest drop in the share in total energy use were reported by services industries. In particular, the strongest rise was reported by 23 Education, Health and Other Services and the most severe drop by 22 Public Administration. These results are in line with previous analyses on total energy use in Brazil conducted at the sectoral level. Thus, Wachsmann et al. (2009) found that the major contributor to the changes in energy use of Brazil over the period 1970–1996 were manufacturing, construction and transport while the contribution of the service sector was more modest. The most recent study by Montoya et al. (2021) confirms that industry and services were the aggregates with the greatest energy footprint in Brazil.

Concerning the distinction between domestic and foreign origin of the energy used, we can observe the existence of some common features among those industries that are the top energy users. Thus, in 19 Transport, 4 Food & Beverages, and 13 Electricity, Gas, and Water, the importance of the energy used and produced in Brazil was much higher than the average in 2015 (85.6%, 84.5% and 94.5%, respectively, compared to 80.6%). In contrast, the domestic use of energy produced abroad was below the average in 2015 (5.4%, 9.6% and 5.4%, respectively, compared to 13.3%). In other words, strong energy users are highly dependent on domestic energy production.

We can highlight the existence of other industries where the domestic use of energy produced abroad plays a key role. These are the industries of 5 Textiles and Wearing Apparel, 9 Electrical and Machinery, 10 Transport Equipment and 14 Construction. In these four industries the domestic use of energy produced abroad accounted for more than 20% of their total energy use in 2015. Some of these industries are characterized by a poor competitiveness and a low degree of integration in global value chains (Callegari et al., 2018; Hollweg and Rocha, 2018). Thus, as Hollweg and Rocha (2018) note in their study of Brazil in global value chains, Brazil has a very weak performance in the industries of Textiles and Wearing Apparel and Electrical Machinery, reporting very low revealed comparative advantages.

5. Conclusions

Recent data from the IEA reveal that Brazil is becoming self-sufficient in energy terms. Its energy exports have risen to the point of surpassing the sum of apparent energy consumption. The aim of this paper was to examine the evolution of total energy use by Brazilian industries over the period 1995–2015. In difference with previous works, we distinguish between the domestic and foreign origin of the total energy used.

The results obtained show a growing importance of the total energy produced in Brazil but used abroad. This confirms the key role of Brazil as world energy provider. The Brazilian production system concentrates its energy use on energy that has a national origin. However, over the last years there was a substantial increase in the energy used for exports. Thus, the pace of growth of the foreign use of energy more than doubled the average growth of the domestic use of energy during the years 1995–2015.

From a sectoral perspective, three industries: 19 Transport, 4 Food & Beverages, and 13 Electricity, Gas, and Water, were found to be the major energy users. These three industries were characterized by an intensive use of energy produced in the own country. In contrast, some service industries, like 15 Maintenance and Repair, 16 Wholesale Trade and 17 Retail Trade, were found to be the weakest energy users.

The dependence of certain activities from global value chains and external trade was reflected into a rising importance of the domestic use of energy produced abroad. This was the case of 5 Textiles and Wearing Apparel, 9 Electrical and Machinery, 10 Transport Equipment and 14 Construction.

In brief, we can affirm that to estimate the total energy use of the different industries and to identify the origin of the energy used is essential for an adequate formulation of energy policies. The production system is a key agent to achieve the transition to more socially and environmentally sustainable energy systems. Nonetheless, it is necessary to take into account that he industries that compose the production system show different energy use patterns. In the case of Brazil, for one part, we found that a reduced group of industries accounts for most of the domestic use of energy produced in Brazil. Sectoral measures, like fostering the introduction of efficient and clean technologies, should be aimed at this specific group of industries. For the other part, we identified the existence of some industries that are increasing reliant of energy produced abroad. This fact extends the problem of mitigation of energy related GHG emission from the national to the global level. To ensure the sustainability of the energy system it is necessary to enhance the energy efficiency across the different global supply chains.

Obviously, our study has limitations. First, as was noted in the introduction, there is considerable time lag in the release of MRIO tables and MRIO models assume hypotheses on homogeneity, proportionality, and imports. Updated MRIO tables could show a more actual picture of total energy use. Second, energy conversion efficiencies could be incorporated to deal with secondary energy production. In addition, sectoral disaggregation is not detailed enough to capture the heterogeneity of products within the different industries. In this sense, the use of commodity-by-industries energy models could be useful in this sense. We also have to note that we have not included household energy use. It also would be interesting to identify the major embodied energy partners. All these issues should be object of study in future works.

Table A.1
List of the 26 industries included in the Eora database.
Source: Own elaboration based on Eora (2019).

Industry	Code
Agriculture	1
Fishing	2
Mining and quarrying	3
Food & beverages	4
Textiles and wearing apparel	5
Wood and paper	6
Petroleum, chemical and non-metallic mineral products	7
Metal products	8
Electrical and machinery	9
Transport equipment	10
Other manufacturing	11
Recycling	12
Electricity, gas and Water	13
Construction	14
Maintenance and repair	15
Wholesale trade	16
Retail trade	17
Hotels and restaurants	18
Transport	19
Post and telecommunications	20
Financial intermediation and business activities	21
Public administration	22
Education, health and other services	23
Private households	24
Others	25
Re-export & re-import	26

CRediT authorship contribution statement

Mercedes Rodríguez: Visualization, Writing – review & editing. **José A. Camacho:** Conceptualization, Methodology, Supervision, Funding acquisition. **Lucas da Silva Almeida:** Writing – original draft, Investigation, Validation. **Jesús Molina:** Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See Table A.1.

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