RESEARCH ARTICLE

The drivers of energy-related CO_2 emissions in Brazil: a regional application of the STIRPAT model

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Abstract

Since energy is one of the basic inputs for development, emerging economies should make an effort to investigate the environmental impacts of their fast economic growth. However, large emerging economies present significant regional heterogeneity that is usually uncounted for. This study uses the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model and regional data on the 27 Brazilian states to investigate the growth-CO_2 nexus under distinct development stages. To perform this analysis, we divided the states into three groups according to their average annual GDP (i.e., richer, intermediate, and poorer regions). The results suggest that richer and poorer regions, particularly, present economic and demographic developments that are environmentally costly. Also, population and per capita GDP have the largest influences on CO_2 emissions. The roles of the industrial sector and the ascending service sector are also subject to criticism. Moreover, Brazil arguably suffers from technological stagnation as its energy intensity is growing and boosting CO_2 emissions. We discuss the policy implications of these findings and suggest a future research agenda.

Keywords CO_2 emissions · Energy · STIRPAT · Latin America · Brazil · Regional analysis

Introduction

From a historical perspective, human societies have a purely extractive relationship with nature (Camioto et al. 2018). However, recent attention is being given to the relationships between economic and population transformations and global warming (Alam et al. 2016; Chishti et al. 2020; Rüstemoğlu and Andrés 2016; Wang et al. 2018) since energy can be considered to be one of the basic inputs for production, similar to capital and labor (Alam et al. 2016). Accordingly, development can be environmentally costly.

Since the 1970s, the Brazilian economy has gone through enormous changes such as infrastructure investments; the development of production capacities regarding capital goods, energy, and transport (among others) (de Freitas and Kaneko 2011; Hewings et al. 1989); and the market opening phenomenon during the early 1990s (Bresser-Pereira and Theuer 2012). Despite these promising development strategies, the

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environment and the energy-related challenges that Brazil and Latin America may be facing (e.g., energy intensity and emissions) are largely ignored (Camioto et al. 2018; Camioto et al. 2016; de Freitas and Kaneko 2011).

Historically, Brazil experienced major electricity challenges with the "apagão" issue that caused the country to experience multiple blackouts (1999 and 2002) due to electricity supply issues (IAEA 2006). These problematic episodes occurred due to many reasons, including inter alia the rapid population increase in recent years, along with increased production, and therefore demand increments (e.g., fuel, electricity, food, appliances, and other items). Consequently, electricity and the overall energy issue gained relevance and led the Brazilian government to invest in new energy sources, such as hydropower energy, which continued to grow considerably (de Freitas and Kaneko 2011; Henriques et al. 2010). Hence, the Brazilian energy matrix became relatively clean (Camioto and Rebelatto 2015; Gouvello 2010), although a thorough discussion on other energy-related issues (e.g., energy intensity, efficiency of energy-saving policies) is often disregarded by the literature and policymakers (Camioto et al. 2018; Henriques et al. 2010).

Within this discussion, we argue that limited attention is given to carbon dioxide (CO_2) emissions since the country's energy matrix and its relatively low impact are usually taken for granted. Nonetheless, emissions are growing along with fossil fuels, vehicles, and energy consumption (Camioto et al. 2018; de Freitas and Kaneko 2011; Rüstemoğlu and Andrés 2016; Ullah et al. 2020). Due to focusing on the hydropower argument (and more recently on biofuels), Brazil gives little attention to problems such as energy conservation, intensity, or emissions (de Freitas and Kaneko 2011).

Evidently, multiple CO_2-related studies in Brazil exist. Yet, the majority of those studies focus on more general aspects of the economic growth and energy consumption connections with CO_2 emissions. These studies usually employ country-level data, such as Hdom (2019), Hdom and Fuinhas (2020), and Pao and Tsai (2011), and sometimes are interested in Brazil for the country's role in the BRICS, such as Khan et al. (2020) and Chishti et al. (2021). Regarding regional-level studies, most researchers are interested in flexible-fuel vehicles, biofuel consumption, and the impact of the transport sector in general (Gerber Machado et al. 2020; Lopes Toledo and Lèbre La Rovere 2018; Santos et al. 2018). More recently, some researchers began studying the impacts of lockdown and the Covid-19 restrictions on the environment using municipal-level data (Dantas et al. 2020; Siciliano et al. 2020). Still, the literature regarding the country's development and CO_2 emissions is limited, particularly from a regional standpoint. To our knowledge, no previous research investigated regional CO_2 emissions within Brazil while considering the regions' distinct development levels. Differences in other countries' development levels have been considered by previous researchers on

both national (Li and Lin 2015; Poumanyvong et al. 2012) and regional levels (Gao et al. 2016; He et al. 2017; Lv et al. 2019), but Brazil's subnational inequalities and disparities are largely ignored by CO_2 studies. Our study attempts to fill this gap by including demographic, economic, and technology-related features in the discussion, in conjunction with the Brazilian states' heterogeneous development levels.

This discussion is of great importance for Brazil, considering that the country's unequal development is well-documented, and it is a product of unequal access to education, distinct productivity levels, industry agglomeration, access to credit, and public policies (Barufi et al. 2016; Costa et al. 2018; Randolph 2019; Santos 2018). He et al. (2017) comment about the new economic geography and how distinct development levels result in contrasting energy efficiency use, urbanization levels, and consumption patterns, in addition to a transformation in the industrial structure that could lead to the optimization of resource allocation. Therefore, considering Brazil's recent development, an investigation on regional heterogeneity and CO_2 is necessary and valuable to the current literature on emerging economies and the environment.

Hence, due to Brazilian regional heterogeneity, we follow previous researchers in studying CO_2 emissions on a regional level (Fang et al. 2019; Gan et al. 2020; He et al. 2017; Wang et al. 2016a; Wang et al. 2016b; Wang et al. 2020; Wang et al. 2017b; Yang et al. 2018; Zhou and Liu 2016). The economic history of Brazil resulted in regions developing at different paces, generating large economic and demographic discrepancies across the country (Ferreira Filho and Horridge 2006; Ribeiro et al. 2020). From this perspective, with researchers arguing that development should be studied regionally, we extend this argument to CO_2 emissions so that economic and population-related environmental impacts may vary depending on the analyzed region. Moreover, the Brazilian industry is facing a downturn and is losing its relative importance while the service sector is growing. These issues should be considered from a regional perspective in order to better comprehend these effects and propose policies to facilitate Brazil's sustainable development.

Theoretical background

The drivers of CO_2 emissions and the role of regional heterogeneity

A large body of literature already attempted to better understand the drivers of CO_2 emissions. This abundance of research has brought forth economic growth and population dynamics as the key determinants of CO_2 emissions at varying scales (Wang et al. 2019b). By reviewing 175 studies between 1995 and 2017, Mardani et al. (2019) found that economic growth is arguably the major variable affecting CO_2

emissions. De facto, economic growth raises the standard of living of a region, thus generating higher CO_2 emission levels. Accordingly, previous studies have shown that economic growth is a powerful determinant of CO_2 emissions (Li and Lin 2015; Wang et al. 2017a; Wang et al. 2019b; Xu et al. 2017a). Moreover, population increases and higher urbanization levels boost energy consumption. As such, previous studies have shown how population dynamics influence CO_2 emissions (Li and Lin 2015; Wang et al. 2017a; Wang et al. 2019b; Zhou et al. 2018).

In addition to more traditional socioeconomic characteristics, other determinants have been presented by the CO_2-related literature, particularly when researchers are employing the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model (Khan et al. 2020; Li and Lin 2015; Lv et al. 2019; Poumanyvong et al. 2012; Wang et al. 2019b; Wu et al. 2019; Xu et al. 2017a; Zhou and Liu 2016). After all, rapid economic growth will generate changes in the industrial structure, energy consumption patterns, and energy intensity (Liao et al. 2019; Lv et al. 2019; Wu et al. 2019). For example, the population living in richer regions will demand more manufactured goods (Li and Lin 2015), which indirectly increases CO_2 emissions. Also, higher levels of industrial output will evidently generate more CO_2 (Li and Lin 2015), and the same can be declared for the service sector (Wang et al. 2020). Highly urbanized and industrialized areas demand a well-developed transport sector, and many researchers have found that this sector generates a significant amount of CO_2 (Gerber Machado et al. 2020; Lv et al. 2019; Poumanyvong et al. 2012).

Furthermore, recent studies are accounting for additional features such as the regions' age structure (Pan et al. 2021), technological progress (Wang et al. 2019c), financial development (Khan et al. 2018), and foreign investments (Zhang and Zhou 2016; Zhou et al. 2018; Polloni-Silva et al 2021b) into the traditional growth-CO_2 nexus. Therefore, analyzing CO_2 emissions is becoming a more complex challenge. The abundance of studies has shown that CO_2 studies present distinct results depending on the region and period chosen, while also depending on the employed method.

Amid this discussion, some researchers defend that regional characteristics need to be considered to better develop mitigation measures. These researchers argue that the drivers of CO_2 emissions given by the literature may present distinct effects under different development levels (Gao et al. 2016; He et al. 2017; Li and Lin 2015). One example is the results from Wang and Zhao (2015) in China showing that urbanization and industrialization present higher impacts on the environment in underdeveloped regions. Also, Poumanyvong et al. (2012) argue that at higher levels of income (i.e., higher development levels), the demand for public transportation decreases, while the demand for private automobiles increases. Wang et al. (2017a) claim that the

development of the industrial and service sectors also changes across regions, as these sectors will have to adjust to distinct policies.
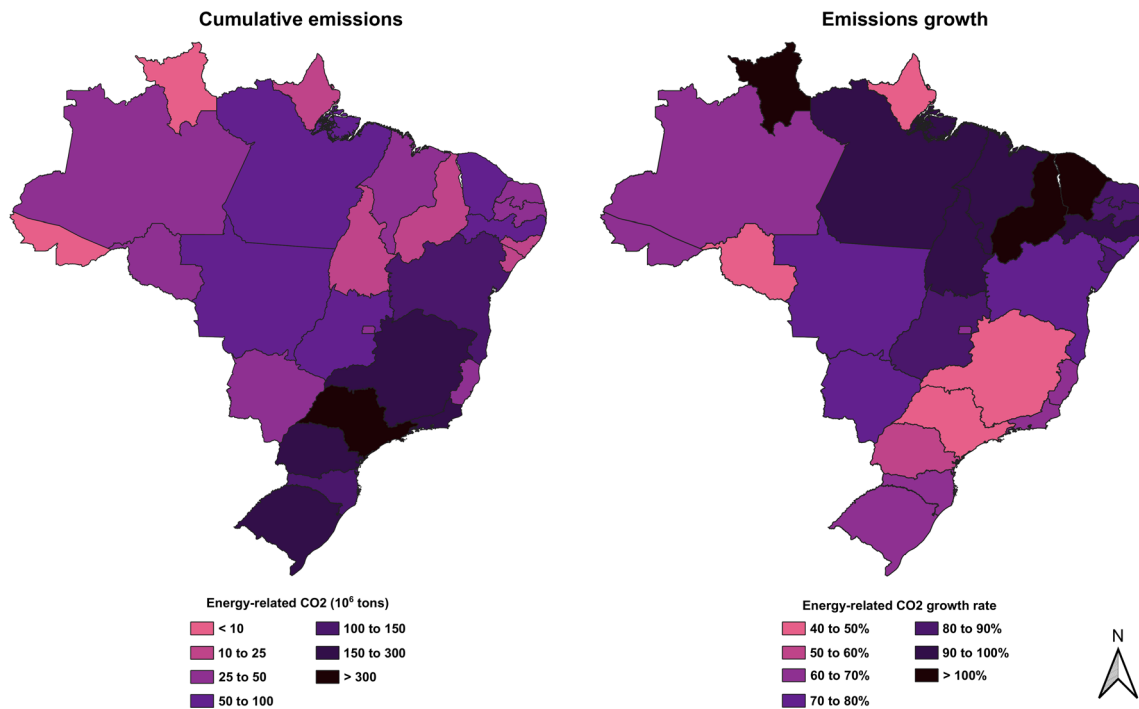
The research done in China by Wu et al. (2019) shows that some regions (i.e., high economy and high carbon intensity) presented the industrial structure as the main driver of CO_2 emissions, while all other regions were mostly affected by population, energy intensity, and GDP. He et al. (2017) showed that Chinese regions with high levels of GDP per capita were highly affected by population, affluence, and the industrial sector and were not affected by the urbanization level, while intermediary and poorer regions presented distinct results for urbanization. Using data from 73 countries, Li and Lin (2015) also showed that the effects of population, affluence, industrial structure, energy consumption, and urbanization change under different development levels. Still, regional-level research that considers distinct development levels are limited (He et al. 2017).

Therefore, new investigations are necessary, and many researchers defend that ignoring subnational differences may result in misleading findings and generate inaccurate policy discussions (Gao et al. 2016; Wang et al. 2017a; Wang et al. 2013). In China, Gao et al. (2016) and Wu et al. (2019) argue that given the vast geographic scale and diverse regional aspects, strategic comprehension of the CO_2 emissions and their drivers is necessary to generate an efficient emission reduction agenda. We argue that Brazil, similar to China, is a large country with significant subnational differences that needs a regional-level analysis regarding its growth-CO_2 relationship.

Evolution of CO_2 emissions and regional heterogeneity in Brazil

Once more, we argue that Brazil is considerably heterogeneous. Figures 1 and 2 highlight these differences. Figure 1 shows the cumulative CO_2 emissions during the studied period (from 2006 to 2015) and the increase in emissions by comparing the 2015 emission levels with those in 2006. Figure 2 shows the evolution of each variable in more detail.

Figure 1 shows that the regional CO_2 emissions were higher in the southeast/south regions of Brazil, which include many of the Tier 1 states. The most polluting region (at least during the 2006–2015 period) was the state of São Paulo. This makes sense since São Paulo is the most important region when economic and population factors are considered. More specifically, São Paulo was responsible for 32% of the country's GDP in 2015, as well as approximately 28% of the total electricity consumption. Rio de Janeiro and nearby regions are also of great importance to the country's economy (e.g., Santa Catarina and Espírito Santo). This is probably the reason why the few energy-related studies in Brazil usually focus on this area (Gandhi et al. 2017; Sant'Anna de Sousa Gomes et al. 2019; Santos et al. 2019).

Cumulative emissions

Emissions growth

Energy-related CO2 (10⁶ tons)

< 10	100 to 150
10 to 25	150 to 300
25 to 50	> 300
50 to 100	

Energy-related CO2 growth rate

40 to 50%	80 to 90%
50 to 60%	90 to 100%
60 to 70%	> 100%
70 to 80%	

Fig. 1 Cumulative CO_2 emissions (left side; from 2006 to 2015) and the 2015 CO_2 emissions compared to 2006 (right side; growth rate)

However, Fig. 1 also shows that the originally less polluting regions (e.g., Roraima, Amapá, Piauí, and Ceará) presented enormous CO_2 emission growth during the studied period. Some of these regions more than doubled their annual emissions during the studied period (2006–2015). Therefore, the lack of attention given to those regions is worrisome since

they present an exceptional CO_2 growth and may need their own studies and policymaking considerations.

Likewise, Fig. 2 demonstrates the annual growth of each variable in the overall sample, as well as in the subgroups, compared to 2006. Energy-related CO_2 emissions are the variable that presented the largest growth during our research
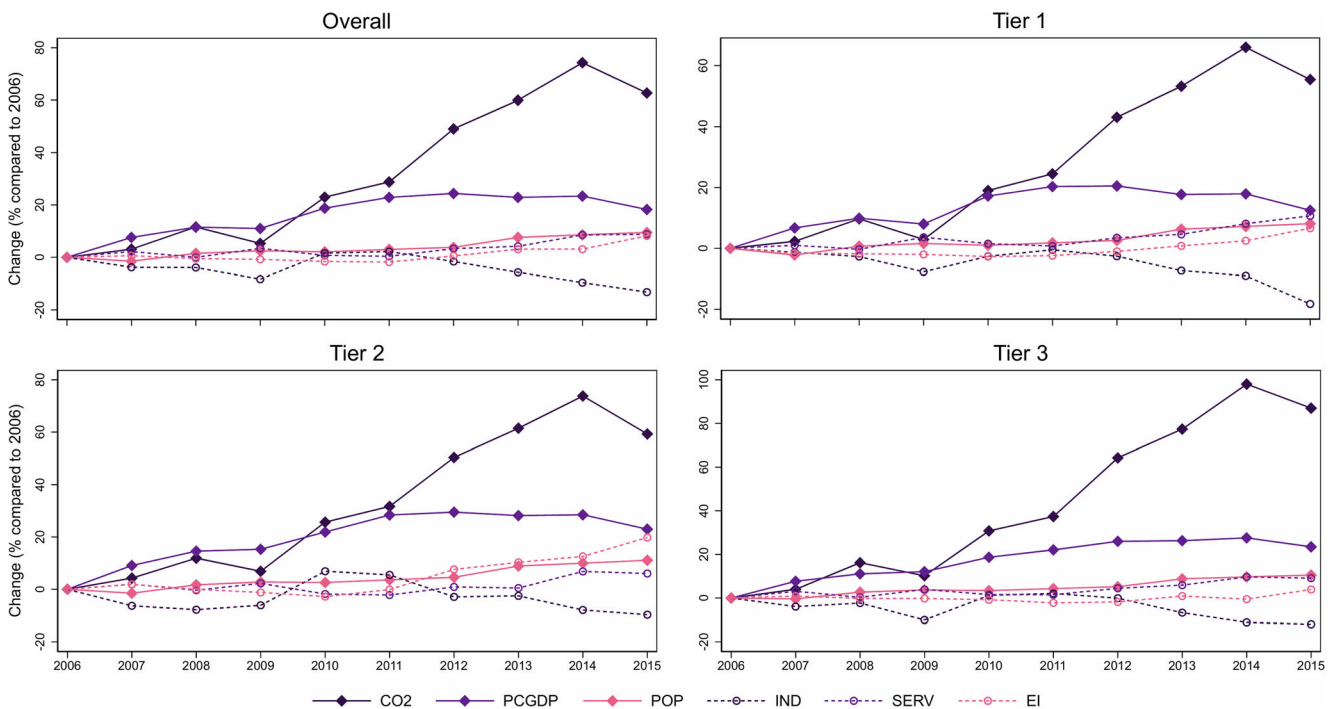
Fig. 2 Change rate compared to the initial period (2006 = 0)

period. Indeed, this raises the question regarding whether the economic growth of Brazil is environmentally friendly or environmentally costly.

The real per capita GDP increased for all regions, although the increases were larger for the Tier 2 and Tier 3 regions. After all, these regions are behind (i.e., underdeveloped) when compared to the richest portion of the country and are now trying to catch up. We also see a large population increase for all regions. As commented previously, the industrial sector is losing its relative importance, and this is true for all regions. In addition, the service sector seems to be gaining importance for all regions, especially the richest Tier 1 states. Finally, energy intensity does not show much variation for the initial research period. However, energy intensity has increased in the last few years, which may raise a serious obstacle for sustainable growth. The last years of our time span show larger energy intensity levels for Tier 1, 2, and 3 regions compared to 2006. This causes the growth strategy of Brazilian regions to be questioned (and this issue will be further discussed in this paper).

Research method

Sample

This study gathered data for all 27 states (also called "federative units") of Brazil for the period from 2006 to 2015. As previously commented, Brazil's history results in contrasting developmental stages across regions, with some states such as São Paulo, Rio de Janeiro, or Rio Grande do Sul being well-developed regions while many states still struggle to catch up. Thus, following the previous literature (He et al. 2017; Wang et al. 2017b; Zhou and Liu 2016), we study how regional heterogeneity influences the drivers of CO_2 emissions.

Following He et al. (2017), who split the sample according to the regions' per capita GDP levels, we split our sample into three additional subgroups using the average real per capita GDP (2006–2015), as presented in Fig. 3. Tier 1 regions represent well-developed states (per capita GDP $\geq$ 30,000 Brazilian reais (BRL)/year), Tier 2 represents regions with intermediate development levels (between 20,000 and 30,000 BRL/year), and Tier 3 represents the least developed regions ($\leq$ 20,000 BRL/year). All GDP-related data were deflated using 2015 as the base year. We argue that this procedure is better than the traditional geography-based sub-sampling (e.g., north/south regions) since it facilitates understanding the complex population/affluence/technology-CO_2 nexus in different development stages.

Energy-related CO_2 emissions

The dependent variable represents the CO_2 emissions from energy consumption. This includes both electricity and fossil fuels. However, since a detailed CO_2-related database is not yet available (at least considering the scope of this study), we manually calculated the emissions per state per year. This procedure is indeed common in STIRPAT studies (Wang et al. 2017a; Wang and Zhao 2015; Wen and Li 2020; Yang et al. 2018).

Data on total electricity consumption (i.e., residential, industries, services, public buildings, street lighting, etc.) were taken from the annual statistical reports of the Energy Research Office (*Empresa de Pesquisa Energética* — EPE). Additionally, we included the consumption of automotive gasoline, diesel oil, liquefied petroleum gas, aviation gasoline, and aviation kerosene. The fuel data were taken from the National Agency for Petroleum, Natural Gas and Biofuels (*Agência Nacional do Petróleo, Gás Natural e Biocombustíveis* — ANP).

Considering the Brazilian fuel market and the Intergovernmental Panel on Climate Change (IPCC 2006) guidelines, we did not consider CO_2 emissions from biodiesel or ethanol. Ethanol is mixed with gasoline "A" to be sold as gasoline "C," and the ratio of ethanol to gasoline changes yearly. Moreover, since 2008, mixing biodiesel with diesel oil became mandatory, and the ratio also changes constantly. We deducted both from our calculations.

Additionally, we employ the electricity-CO_2 conversion factors published by the Ministry of Science, Technology, Innovation, and Communications (*Ministério da Ciência, Tecnologia, Inovações e Comunicações* — MCTIC). The Brazilian government considers all electricity sources (i.e., hydro, natural gas, oil, biomass, coal, wind, nuclear, and solar) contributing to the national grid to define the CO_2 conversion factor. As presented in Fig. 4, Brazil's electricity-related CO_2 impact is comparatively low due to the country's dependency on hydropower (see Appendix Fig. 6), with an average of 0.06362 TCO$_2$/MWh. Comparatively, the 2013 conversion factor for the UK and the EU-28 countries were 0.503 and 0.373 TCO$_2$/MWh, respectively (Koffi et al. 2017). For the selected fuels, the conversion factors are given in Table 1.

STIRPAT model

The IPAT model (Ehrlich and Holdren 1971) that originally suggested studying environmental impacts (I) using the information on the population (P), affluence (A) and technology (T) is presented in Eq. (1).

$$I = P \times A \times T \tag{1}$$

However, to analyze one factor, the other two must remain unchangeable, which is of no use for the integrated analysis of

Fig. 3 Distribution of regions according to their average annual per capita GDP (2006–2015)
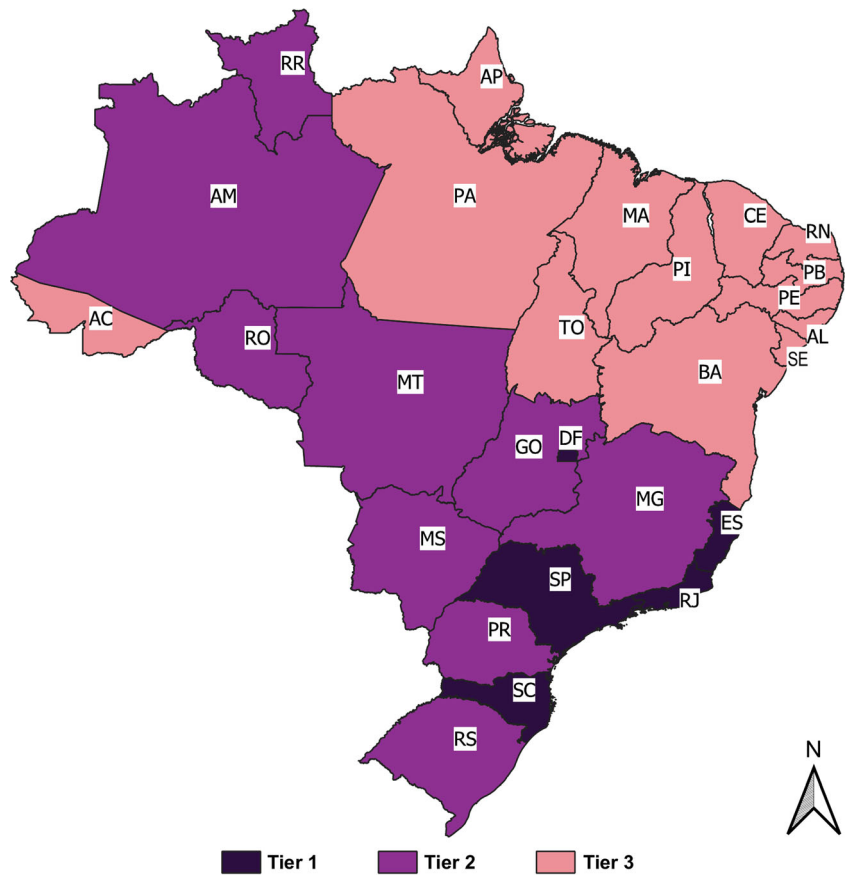
Tier 1: Distrito Federal (DF), Espírito Santo (ES), Rio de Janeiro (RJ), Santa Catarina (SC), São Paulo (SP).
Tier 2: Amazonas (AM), Goiás (GO), Mato Grosso (MT), Mato Grosso do Sul (MS), Minas Gerais (MG), Paraná (PR), Rio Grande do Sul (RS), Rondônia (RO), Roraima (RR).
Tier 3: Acre (AC), Alagoas (AL), Amapá (AP), Bahia (BA), Ceará (CE), Maranhão (MA), Pará (PA), Paraíba (PB), Pernambuco (PE), Piauí (PI), Rio Grande do Norte (RN), Sergipe (SE), Tocantins (TO).

all three factors simultaneously. Therefore, Dietz and Rosa (1997) suggested the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model in Eq. (2).

$$I = aP^b A^c T^d e \qquad (2)$$

It can be rewritten in its logarithmic form as Eq. (3).

$$\ln I = a + b\ln P + c\ln A + d\ln T + e \qquad (3)$$

From this point on, researchers started to analyze multiple factors at once while including additional variables to further comprehend the possible factors influencing the environmental
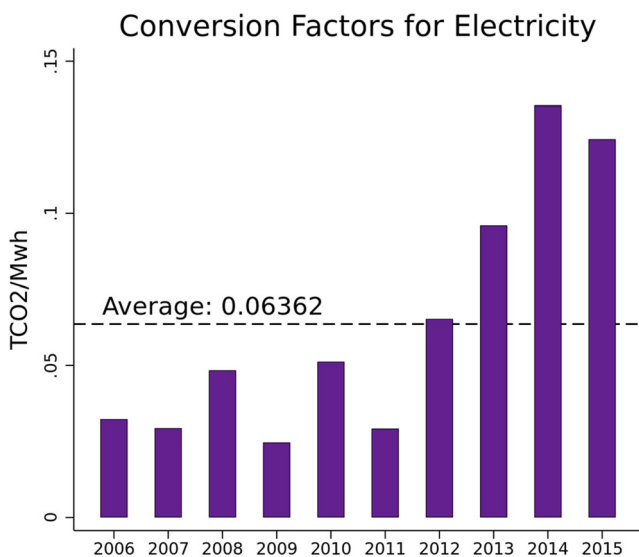
Fig. 4 Annual electricity-CO_2 conversion factors

Table 1 Conversion factors

Fuel	TCO_2/TJ
Automotive gasoline	69.3
Diesel oil	74.1
Liquefied petroleum gas	63.1
Aviation gasoline	70
Aviation kerosene	71.5

Source: IPCC (2006)

impacts, as long as these variables are conceptually appropriate for the multiplicative specification of the model. In this study, our model can be written as presented in Eq. (4).

$$\ln CO2_{it} = \beta_0 + \beta_1 \ln PCGDP_{it} + \beta_2 POP_{it} + \beta_3 \ln IND_{it}$$
$$+ \beta_4 \ln SERV_{it} + \beta_5 \ln EI_{it} + a_i + e_{it} \qquad (4)$$

Here, CO2 is the energy-related CO_2 (tons), PCGDP is the real per capita GDP, POP is the population size, IND is the industrial sector (% of GDP), SERV is the service sector (% of GDP), EI is the energy intensity (electricity consumption per unit of the industrial and service sectors' GDP), β_0 is the intercept, β_1 to β_5 are the coefficients for each respective explanatory variable, i is the specific region, t is the specific year, a_i is the regional fixed effect, and e is the error term. Drawing from the original IPAT model, POP represents the population (P); PCGDP represents affluence (A); and IND, SERV, and EI represent the facets of the regional technological level (T).

Here, the explanatory variables (economic and population-related data) were taken from the Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística* — IBGE).

Data pre-testing and estimation strategy

Initially, we implemented the Pesaran (2004) CD test for cross-sectional dependence across the Brazilian states included in the dataset. The idea of cross-sectional homogeneity is violated when different regions share common shocks regarding trade and other economic issues, or similar institutional or technological developments (Keho 2018). In other words, cross-sectional dependence is the result of unobservable and/or observed common factors to all regions (Ertur and Musolesi 2017). Table 2 shows that the null hypothesis of cross-sectional independence is rejected for all variables and subsamples.

As this research uses panel data, it is necessary to verify if the variables are stationary, as nonstationary series may lead to spurious regressions (Granger and Newbold 1974; Wang et al. 2019a, 2019b, 2019c). Unit root tests are generally used to check the stationarity of the data. We applied two panel unit root tests, namely the Levin-Lin-Chu (LLC) (Levin et al. 2002) and the Im-Pesaran-Chin (IPS) (Im et al. 2003) tests. Both tests are commonly employed in econometric studies, and while the LLC is based on a common root test, the IPS considers individual root tests (Wang et al. 2019a). Table 3 shows the results for the LLC and IPS tests for all groups (overall and Tiers 1–3). All variables are stationary at first difference.

As shown in Table 3, all variables stationary in the same order. Thus, the next step is to determine the degree of integration of the series using a panel cointegration technique.

Salman et al. (2019) and Hdom (2019) argue that ordinary cointegration tests (e.g., Pedroni cointegration test) may produce biased estimates when there is cross-sectional dependence among the variables. Therefore, we employ the Westerlund (2005) panel cointegration test to evaluate the long-run linkage among all variables using distinct test statistics. The group statistics test if some panels are cointegrated using the group-mean variance ratio (VR) statistic. The panel statistics test if all panels are cointegrated using the panel VR statistic.

With the results of Table 4, we conclude that long-term relationships exist among the variables included in our models.

Furthermore, we verified if multicollinearity was an issue in our models since it is somewhat common for STIRPAT models to present some level of collinearity between its variables. To avoid this issue, we split our models into two forms: one including the industrial sector and another including the service sector. The results are presented in Table 5, which shows that collinearity is not an issue since no variance inflation factor (VIF) is higher than 10. Furthermore, the

Table 2 CD tests

Variables	Overall		Tier 1		Tier 2		Tier 3	
	CD test	Abs	CD test	Abs	CD test	Abs	CD test	Abs
CO2	57.43***	0.969	14.43***	0.996	13.78***	0.951	27.01***	0.967
PCGDP	44.20***	0.747	10.78***	0.744	9.80***	0.676	22.08***	0.790
POP	54.54***	0.921	13.12***	0.905	13.68***	0.944	25.73***	0.921
IND	15.62***	0.417	6.95***	0.495	3.95***	0.439	5.00***	0.358
SERV	26.23***	0.501	9.36***	0.646	7.74***	0.534	8.31***	0.458
EI	13.78***	0.459	3.28***	0.361	3.02***	0.581	4.66***	0.448

Abs average absolute correlation coefficient

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

Table 3 Panel unit root tests

Sample	Variable	Levin-Lin-Chu (LLC)		Im-Pesaran-Shin (IPS)	
		Level	1st diff.	Level	1st diff.
Overall	CO2	−4.6160***	−14.6987***	0.8475	−5.0023***
	PCGDP	−12.2224***	−16.7532***	1.8803	−5.6605***
	POP	−21.4369***	−25.5390***	−3.6234***	−11.4201***
	IND	−5.9951***	−12.6253***	1.3371	−3.6329***
	SERV	−7.0508***	−20.4115***	0.4624	−9.1993***
	EI	−5.8607***	−15.4939***	1.2812	−4.9025***
Tier 1	CO2	−2.4407***	−7.1712***	0.4170	−2.5250***
	PCGDP	−0.6840	−7.0977***	2.6555	−2.1834**
	POP	−20.7308***	−10.6040***	−6.1719***	−4.4664***
	IND	−1.6527**	−5.4657***	1.5392	−2.1921**
	SERV	−4.4262***	−9.7215***	−0.0815	−3.9883***
	EI	−0.7600	−9.6301***	1.4344	−3.3573***
Tier 2	CO2	−0.9426	−6.1967***	1.2223	−1.3837*
	PCGDP	−1.4470*	−6.5338***	2.6835	−1.8129**
	POP	−3.0309***	−12.8226***	−0.3945	−6.1609***
	IND	−3.5160***	−6.4912***	0.3145	−1.9964**
	SERV	−0.8212	−11.7322***	1.7811	−6.1492***
	EI	−4.0868***	−8.6589***	0.3201	−2.9340***
Tier 3	CO2	−4.0985***	−11.4462***	0.0103	−4.3410***
	PCGDP	−12.9175***	−13.3570***	−1.1965	−5.2252***
	POP	−4.1738***	−19.3688***	−0.4694	−8.6599***
	IND	−4.7468***	−9.4247***	0.5733	−2.9336***
	SERV	−5.9617***	−13.5799***	−0.6457	−5.8188***
	EI	−4.6855***	−8.8230***	0.5778	−2.4487***

Akaike information criterion (AIC) used to select the optimum lag length. The tests employed an intercept and trend specification. Variables were used in their natural-log form

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

correlation and distribution of all variables can be seen in detail in Appendix Fig. 7.

To decide which estimation technique should be employed on our dataset, Hausman tests were used to evaluate which specification (i.e., random of fixed effects) is preferred. The results show that a fixed-effects specification should be employed. Yet, traditional fixed-effects estimations may produce biased results

if other nonspherical disturbances are also present. Therefore, we employed the modified Wald test for groupwise heteroskedasticity (Greene 2002) and the Wooldridge test for autocorrelation (Wooldridge 2010). The results suggest that autocorrelation and heteroskedasticity are found in the overall sample and sub-samples. Additionally, as presented earlier, cross-sectional dependence is an issue. With these tests, it is possible

Table 4 Westerlund cointegration tests

Test	Overall		Tier 1		Tier 2		Tier 3	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Panel	2.3886***	2.9123***	1.7080*	1.8428**	1.0136	1.1499	1.7687**	2.1417**
Group	5.995***	5.6828***	2.7992***	3.4064***	2.3977***	1.6763**	4.8327***	4.4601***

Akaike information criterion (AIC) used to select the optimum lag length. The tests employed an intercept and trend specification. Model 1 includes the industrial sector, and model 2 includes the service sector. Variables were used in their natural-log form

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

Table 5 Multicollinearity tests

Variables	Variance inflation factor (VIF)							
	Overall		Tier 1		Tier 2		Tier 3	
PCGDP	2.48	2.49	7.12	6.65	1.48	1.45	1.48	1.28
POP	1.55	1.81	1.29	4.67	5.16	1.83	2.09	1.59
IND	1.47		4.28		5.88		1.84	
SERV		1.78		4.06		2.74		1.31
EI	2.38	2.35	4.78	5.15	2.74	1.66	1.35	1.39
Mean	1.97	2.11	4.37	5.13	3.82	1.85	1.69	1.39

to assure consistent estimations for each subgroup. The results of these tests can be seen in Appendix Table 8.

The overall sample and the Tier 3 group showed significant test statistics for groupwise heteroskedasticity, autocorrelation, and cross-sectional dependence. Additionally, both groups (overall and Tier 3) present an $N > T$ arrangement. These issues make it unadvisable to adopt several estimation techniques such as the Feasible Generalized Least Squares (FGLS) (Parks 1967), which is not reliable when the cross-sectional dimension N is larger than the time dimension T; the Panel-Corrected Standard Errors (PSCE), which presents poor results for finite samples and an $N > T$ aspect (Hoechle 2007); or the Newey-West (NW) estimation (Newey and West 1987), which is not able to deal with cross-sectional dependence (Zhang and Zhou 2016). Hence, these two groups (overall and Tier 3) were estimated using the fixed-effects Driscoll-Kraay (DK) standard errors (Driscoll and Kraay 1998). The DK model can be used when it is necessary to deal with some sort of cross-sectional dependence, and it is not restricted by the number or size of panels (Hoechle 2007).

Furthermore, the Tier 1 and 2 groups presented their own sets of nonspherical disturbances. Tier 1 presented both autocorrelation and cross-sectional dependence issues. On the other hand, the Tier 2 group shows heteroskedasticity and cross-sectional dependence issues. As the Driscoll-Kraay estimator assumes that the error structure is heteroskedastic and autocorrelated, an alternative estimation technique should be used to respect each group's specific characteristics. Differently to the overall and Tier 3 groups, Tier 1 and 2 groups present an $N < T$ arrangement. Accordingly, the FGLS technique can be used, and this technique allows the user to define autocorrelation, heteroskedasticity, and cross-sectional dependence issues separately, thus handling the particular nonspherical disturbances of each group (Croissant and Millo 2008; Wooldridge 2010). Yet, as the FGLS traditionally uses random-effects specifications, we added the state-specific dummy variables and excluded the intercept, thus employing a fixed-effects Generalized Least Squares (FE-GLS) estimation, following Wooldridge (2010), Croissant and Millo (2008), and Polloni-Silva et al. (2021a).

In sum, by using DK and FE-GLS estimations, we guarantee that all estimations are consistent and reliable while aligning this research with the estimation strategy of previous studies (He et al. 2017; Wang et al. 2017b; Zhang and Lin 2012).

Results

Main findings

The results are displayed in Table 6, following the adequate estimation technique for each group, as discussed in "Data pre-testing and estimation strategy".

For all regions, the main contributor to CO_2 emissions is the population, which makes sense considering the size of the Brazilian population and its growth. Regarding the overall sample, a 1% increase in the population size generates a 2.4–2.7% increase in CO_2 emissions. Hence, CO_2 emissions are elastic to variations in the population size. Additionally, we see a significant impact from real per capita GDP on emissions. A 1% increase in per capita GDP results in a 1.19–1.23% increase in CO_2 emissions. Hence, both factors are representing population-related CO_2 emissions due to peoples' consumption and purchasing power. The emission levels are sensitive to changes in these variables. Particularly, we see that the impact of real per capita GDP is larger for the Tier 3 (poorer states) group.

Moreover, interesting findings for the relationship between the industrial/service sectors and emissions are found. The majority of STIRPAT studies use industry participation in total GDP to represent technology. In many cases, these studies include regions with a flourishing industry (e.g., China). Here, however, the industrial sector presents a negative effect on CO_2 emissions. The reader should not assume that the Brazilian industry is environmentally friendly. As will be further discussed, industry is losing its relative importance, which is true for all regions. Regarding the service sector, the results are also interesting. The overall sample showed that a 1% increase in the participation in the service sector increases CO_2 emissions by 0.914%. This is particularly worrisome for the Tier 1 (elasticity = 0.662) and Tier 3 (elasticity = 0.900) groups. Thus, the growing presence of service sectors in Brazil's GDP is not free of criticism.

Last, the Tier 1 group, representing the richest and most productive regions of Brazil, showed that its energy intensity enhances CO_2 emissions. Obviously, if more energy is necessary to produce a unit of GDP, more CO_2 emissions can be expected. This shows that the technology being used is not promoting CO_2 reductions. Instead, the region seems to be losing its capacity to effectively use the energy it consumes. The consequences of our findings will be further discussed in the next sections.

Table 6 Estimations for the overall sample and the Tier 1, 2, and 3 groups

Variables	(1) Overall	(2)	(3) Tier 1	(4)	(5) Tier 2	(6)	(7) Tier 3	(8)
	DK-FE	DK-FE	FE-GLS	FE-GLS	FE-GLS	FE-GLS	DK-FE	DK-FE
PCGDP	1.239***	1.193***	1.251***	1.292***	0.818***	0.784***	1.471***	1.331***
	(0.160)	(0.148)	(0.0279)	(0.0427)	(0.0490)	(0.0605)	(0.147)	(0.123)
POP	2.707***	2.455***	2.393***	2.058***	2.713***	2.434***	2.554***	2.473***
	(0.105)	(0.0710)	(0.0863)	(0.108)	(0.103)	(0.114)	(0.148)	(0.127)
IND	−0.339***		−0.120***		−0.186***		−0.340***	
	(0.0987)		(0.00943)		(0.0239)		(0.0882)	
SERV		0.914***		0.662***		0.135		0.900***
		(0.130)		(0.0554)		(0.101)		(0.0962)
EI	0.0199	0.0868	0.643***	0.551***	0.0147	0.130***	0.00614	0.0396
	(0.0903)	(0.0768)	(0.0341)	(0.0545)	(0.0282)	(0.0268)	(0.0991)	(0.0932)
Constant	−28.58***	−28.32***			−28.81***	−25.67***	−26.46***	−28.82***
	(1.952)	(1.263)			(5.150)	(4.822)	(2.186)	(1.428)
F	316.12***	454.14***					127.33***	317.32***
R^2	0.8779	0.8872					0.8842	0.8937
Wald chi^2			34,500,000***	14,400,000***	11,500,000***	5,437,178***		
Observations	270	270	70	70	70	70	130	130
Number of regions	27	27	7	7	7	7	13	13

The standard errors are in parentheses

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

Robustness tests

Although we employ a comprehensive regional dataset on Brazil and apply econometric techniques that address each group's nonspherical disturbances, it is useful to perform robustness tests on our data. Therefore, this section deals with possible endogeneity issues. This procedure is largely ignored by emissions studies. Here, we employ the lagged values of all explanatory variables (Table 7). For instance, last year's production cannot be responsible for this year's CO_2 emissions. The results confirm our primary findings. Again, population and GDP are the main factors affecting CO_2, the service sector is environmentally costly, and energy intensity is not showing a technological transformation that could benefit the environment.

Discussion

Our findings corroborate previous studies on the noteworthy effects of population and per capita GDP on CO_2 emissions (He et al. 2017; Wang et al. 2017a; Zhou and Liu 2016). This is due to the recent population growth in Brazil and the fact that more people results in more household electricity consumption, more fuel consumption, and more consumption of regular goods and technology (e.g., appliances such as air-

conditioning). Brazil presented an overall population growth of 9.5% during the studied period. The Tier 1, 2, and 3 groups experienced growth of 7.2, 10, and 9.7%, respectively. Indeed, the demographic impact on CO_2 emissions will be further complemented by increases in income and overall richness. Real per capita GDP also grew considerably (overall growth of 23.4%), especially in the originally poorer regions (Tier 3; 27.6%). Again, this increased income results in larger consumption of goods (Perobelli et al. 2015). Regions are growing, but this phenomenon does not seem to be sympathetic towards the environment.

Interestingly, we find a negative relationship between the growth of the industrial sector and CO_2 emissions. Here, two observations should be made. First, the industrial sector is indeed losing its relative importance, which is true for all regions, especially after 2010 (see Fig. 5).

Our results should not encourage the reader to assume that the industrial sector is environmentally friendly since the results for the energy intensity show that Brazil's technological efficiency is decreasing. Indeed, industrial production is well known as an important source of CO_2 emissions (Xu et al. 2017b). Additionally, this brings a second observation. Countries facing a deindustrialization process should rethink the commonly employed "industrial sector as % of GDP" approach as a representation of technology in STIRPAT studies. For example, the

Table 7 Estimations with lagged variables

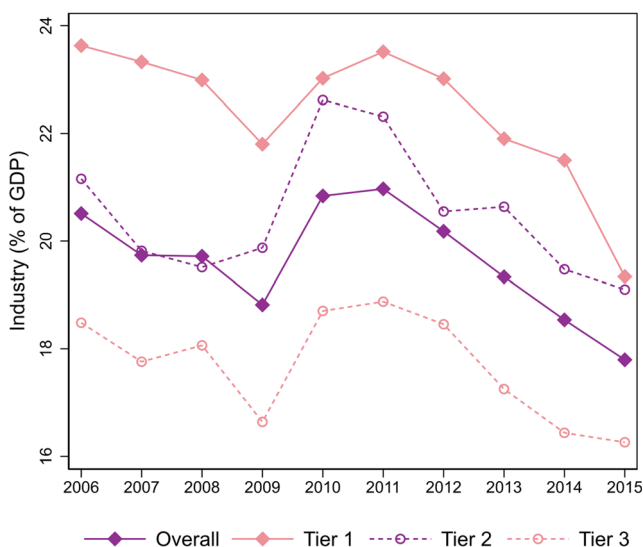| Variables	(17) Overall	(18)	(19) Tier 1	(20)	(21) Tier 2	(22)	(23) Tier 3	(24)
	DK-FE	DK-FE	FE-GLS	FE-GLS	FE-GLS	FE-GLS	DK-FE	DK-FE
$PCGDP_{t-1}$	1.399***	1.334***	1.196***	1.244***	1.005***	1.024***	1.623***	1.440***
	(0.142)	(0.135)	(0.0851)	(0.0777)	(0.0265)	(0.0365)	(0.158)	(0.145)
POP_{t-1}	2.112***	1.956***	2.289***	1.717***	2.014***	1.741***	1.942***	2.025***
	(0.222)	(0.239)	(0.143)	(0.148)	(0.0420)	(0.0804)	(0.365)	(0.372)
IND_{t-1}	−0.0179***		−0.146***		−0.168***		−0.0220***	
	(0.00134)		(0.0417)		(0.0120)		(0.00208)	
$SERV_{t-1}$		0.867***		1.009***	0.202***	0.279***		0.814***
		(0.220)		(0.0650)	(0.0164)	(0.0206)		(0.178)
EI_{t-1}	0.0712**	0.184***	0.549***	0.592***		0.428***	0.0349	0.162**
	(0.0338)	(0.0456)	(0.101)	(0.0563)		(0.0538)	(0.0694)	(0.0615)
Constant	−20.10***	−20.04***					−17.92***	−20.91***
	(3.310)	(3.966)					(5.529)	(5.852)
F	437.04***	70.48***					256.34***	145.99***
R^2	0.8331	0.8418					0.855	0.8551
Wald chi^2			6,423,597***	12,100,000***	11,500,000***	8,927,437***		
Observations	243	243	63	63	63	63	117	117
Number of regions	27	27	7	7	7	7	13	13

The standard errors are in parentheses

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

industrial sector is positively associated with emissions in many Chinese studies. However, Chinese industry is ever-growing. This is not the case for Brazil. Data from the World Bank show that other emerging economies face similar industrial shrinkage (e.g., Argentina, Italy, and the Netherlands and the world average). Thus, deindustrialization may be a problem. Emission-related

Fig. 5 The industrial sector's relative importance

studies should account for that in their model formulation processes.

Furthermore, the service sector, although less affected by tech-related issues, has a significant impact on fuel consumption (Gandhi et al. 2017; Rüstemoğlu and Andrés 2016). São Paulo, one of the Tier 1 regions, still has a strong industrial sector, as well as a growing focus on services and trade (de Miranda et al. 2012). As expected, the Tier 1 region is highly impacted by both the energy intensity issue and the service sector. Ideally, a region will increase its GDP while reducing its energy consumption (Camioto et al. 2016), which is not the case for Brazil. Our results arguably show that the current energy-saving policies are ineffective in reducing the energy intensity. Hence, our results challenge the actions of the Federal and State governments in putting energy-related policies into action. It also shows that Brazil does not have access to cleaner technologies/ practices, which is especially relevant for industrial activities, or a well-developed transport infrastructure, which is paramount for all business activities.

Our findings also corroborate with the idea that regional heterogeneity matters. The Tier 1 region represents the rich states with well-developed economies and good urbanization levels for their large populations. As such, when its GDP or population increases, the CO_2

increases are severe. After all, larger regions may offer better pay, but they do not necessarily have higher productivity rates to compensate for this circumstance (Barufi et al. 2016). In addition, industry loses its importance to services, but neither sector seems to be developing its capabilities to increase its productivity and therefore decrease its energy intensity. Similar aspects are found in poorer regions. Tier 3 states present the same characteristics, but these issues are worsened by these states' attempts to catch up with the richer regions. The results from the main estimations, in addition to the robustness tests, show that both regions are thoroughly expanding their economies and demographic aspects. As commented earlier, some Tier 3 states have more than doubled their annual CO_2 emissions during the 2006–2015 period. In addition to industry-related CO_2, the service sector has a large impact on the environment as a 1% increase in the service sector's GDP generates 0.814% more CO_2. This attempt to rectify historical inequality issues is environmentally costly, and it should not be overlooked only because a large share of Brazilian energy comes from renewable sources.

Amid this discussion, we argue that studying intermediary regions (i.e., medium levels of development) is a difficult task. Although robustness tests show that Tier 2 states are experiencing similar issues regarding the economical, demographic, and technological changes and their effects on CO_2, it is somewhat difficult to find significant coefficients. This was the case for the service sector in Table 6. At least in Brazil, it seems that both richer and poorer countries are investing in rapid growth. However, the intermediary regions are not as consistent in this task. The state of Amazonas, for example, had a volatile per capita GDP during the period and finished 2015 with a lower GDP compared to 2006. Minas Gerais, Rondônia, and Roraima also experienced initial growth but finished the period with GDP decreases. Contrary to most regions, Mato Grosso and Mato Grosso do Sul, which are historically dependent upon agribusiness, are now experiencing industrial growth. Some states are also experiencing losses in the ratio of service sector GDP to total GDP (e.g., Amazonas and Goiás), and relatively small reductions in energy intensity (e.g., Mato Grosso do Sul) are offset by relatively large increases in energy intensity by others (e.g., Roraima and Rondônia). Therefore, studying intermediary regions (represented here by the Tier 2 group) is a task that deserves more attention, and arguably separate studies. Moreover, we show that robust estimations and additional tests only benefit STIRPAT studies.

Conclusion and policy implications

This study attempted to better understand how regions with distinct levels of development evolved and produced energy-related CO_2. This was done with data on the 27 states of Brazil and the STIRPAT model. In summation, the results show that CO_2 emissions are sensitive to changes in population and per capita GDP. Consumption is a major challenge for Brazil and its future CO_2 emissions. Moreover, we see a decrease in the overall economic importance of the industrial sector, which results in negative or insignificant coefficients when CO_2 emissions are used as the dependent variable. Countries facing a deindustrialization process should rethink the "industrial sector as % of GDP" measure as a representation of regional technology. Additionally, the service sector is growing considerably in most regions, and it has a large environmental impact. Likewise, the energy intensity is increasing, which results in larger emissions due to less productivity and technological efficiency. These results have important policy implications.

Tiers 1, 2, and 3 (meaning rich, intermediary, and poor states, respectively) present distinct results. Tier 1 and its richer states present steady growth levels and growing CO_2 emissions and energy intensity, showing that the region's growth is not environmentally friendly. More worrisome, the poorer states (Tier 3) appear to not be holding back in their attempt to catch up with the other regions. Some regions are achieving considerable enhancements in their GDP and demographical aspects, but at what cost? De facto, these regions also presented significant increases in their CO_2 emissions. Regarding the intermediary regions, we find that they are heterogeneous among each other, resulting in research difficulties. In any case, all regions seem to be growing and developing in an environmentally harmful manner. Therefore, policymakers should not neglect the country's poorest areas in future energy-related programs.

Also, close attention should be given to increases in income and the overall richness and consumption of goods. As shown by our results, population and per capita GDP are the main causes of energy-related CO_2 emissions. Perobelli et al. (2015) argue that the private consumption of goods represents a major proportion of the final demand, and even a small variation in consumption can have larger impacts on emissions. Thus, policies aimed to raise awareness of the importance of energy savings from the environmental and energy safety perspectives may be a valuable tool for Brazil,

especially considering that education, among other factors, is unequal across regions.

Additionally, Brazil focused its efforts on diversifying its energy matrix while energy intensity and technological advancements were ignored. The energy-saving policies are positive, but their real impact on Brazilian CO_2 emissions is still dubious. Policies such as the National Electricity Conservation Program (*Programa Nacional de Conservação de Energia Elétrica* — PROCEL; focused on equipment's energy efficiency and the diffusion of energy-saving information), the Energy Efficiency Program (*Programa de Eficiência Energética* — PEE; focused on increasing energy efficiency in all economic sectors), and the Energy Efficiency Law (*Lei de Eficiência Energética* — no. 10.295; focused on industrial and residential energy waste and boosting renewable sources such as solar energy) represent good measures to decrease energy use (and therefore CO_2 emissions). Additional national and regional policies should be establish aiming for a higher impact on energy savings and intensity, particularly at this moment considering that in 2016 Brazil confirmed its commitment to the Paris agreement to lower its greenhouse gas emissions by 37% by 2025 and 43% by 2030 based on 2005 values (Lima et al. 2020).

Accordingly, we agree with Vieira et al. (2018) that any energy efficiency program should involve the industrial sector. Within this scope, another major issue for the Brazilian growth-CO_2 nexus is the lack of technological progress. The lack of financing and technical expertise and the current energy-saving programs are not capable of effectively influencing industry (Henriques et al. 2010). Here, we argue that Brazil should work towards economic sophistication instead of the historical "export of raw goods and import of finished ones" circumstances that affect the country. This task is obviously difficult, especially considering the ongoing deindustrialization process. Gandhi et al. (2017) argue that São Paulo predicted a decrease in its energy intensity from 2000 to 2010, but it failed to deliver on that promise. In this sense, São Paulo exemplifies how Brazilian regions can be similar to developed economies (in its development levels) while presenting the energy-related characteristics of emerging economies. The service sector is not free of criticism either. Evidence points to the service sector being environmentally costly, especially considering its fuel consumption. Diversifying the energy employed by the service sector could prove to be a valuable tool to decrease CO_2 emissions by increasing energy intensity.

In addition to this discussion, Brazil has enormous potential to produce energy from a variety of renewable sources due to its size, insolation, coast, and biodiversity (Lima et al. 2020). Obviously, although using the renewable energy argument to avoid a real discussion of energy-related issues represents a challenge that Brazil needs to overcome, it does not mean that investing in additional renewable energy sources is a bad decision. However, hydropower has its limits. Fortunately, other sources have great potential in Brazil. For example, some studies show that the Brazilian shore shows potential for wind energy. Research shows this is especially the case for the northeast of Brazil (de Jong et al. 2017; Macedo et al. 2017). The region already invests in wind-related energy equipment and research (de Jong et al. 2017). However, in many cases, this field seems to evolve using "baby steps" in Brazil, inter alia due to the country's challenging infrastructure. Still, Barufi et al. (2016) argue that there are many regions in which the wind potential and the demographic density are correlated, meaning that relatively small investments in transmission lines could be widely beneficial.

Furthermore, as commented earlier, alternative fuel sources are already important for Brazil. The country consumes a large amount of ethanol and other biofuels. Yet, challenges exist. Using São Paulo as an example, it is clear that depending on good weather for the region's sugarcane production is not ideal, and a demand for ethanol production processes that do not depend on atmospheric conditions exists, as stated by Gandhi et al. (2017) and Rüstemoğlu and Andrés (2016). Moreover, policymakers should investigate how changes to regulatory standards could benefit the environment by increasing energy efficiency.

A final issue that should be mentioned (and that is not included in the scope of this paper) is the mismanagement and corruption in Brazil. Lin et al. (2017) argue that Petrobras (Brazilian Petroleum Corporation) did not face resource-related problems recently. Instead, the company's struggle is due to mismanagement and corruption. Hence, the authors claim that one possible reason for the growth-CO_2 issue in Brazil is the deep-rooted corruption in the energy sector.

In any case, we argue that any powerful policy targeting CO_2 reduction will likely demand efforts from both public and private parties, as argued by Henriques et al. (2010). A good example is the National Bank for Economic and Social Development (BNDES) in 2013 and its 3 billion (Brazilian real — BRL) fund towards transmission lines, smart power grids, and improving the efficiency of solar/wind sources (Barufi et al. 2016).

Future research agenda

This study showed that the industrial sector can be a complex topic. Therefore, future studies should verify if deindustrialization is a problem in the selected country/region. Many STIRPAT studies are focused on China and its ever-growing industry. However, other emerging economies may present distinct industrial contexts. Additionally, employing sector-specific data on both the industrial and service sectors could lead to precious findings. Moreover, some researchers have argued that energy intensity can be influence by a variety of factors (e.g., economic development, the climate, and energy prices). This issue could be further analyzed. Furthermore, the BRICS countries (and most emerging economies) arguably present contrasting subnational differences that should be considered in regional studies, as stated by Camioto et al. (2016). Corruption may also be an influencing factor for the growth-CO_2 nexus. Last, other environmental issues such as the water footprint, air pollution, and health issues can lead to valuable policymaking discussions. Studying these issues in Brazil may be difficult for many reasons, such as, inter alia, the lack of local-level data. However, future research on these problems is necessary for the sustainable growth of the country.

Appendix
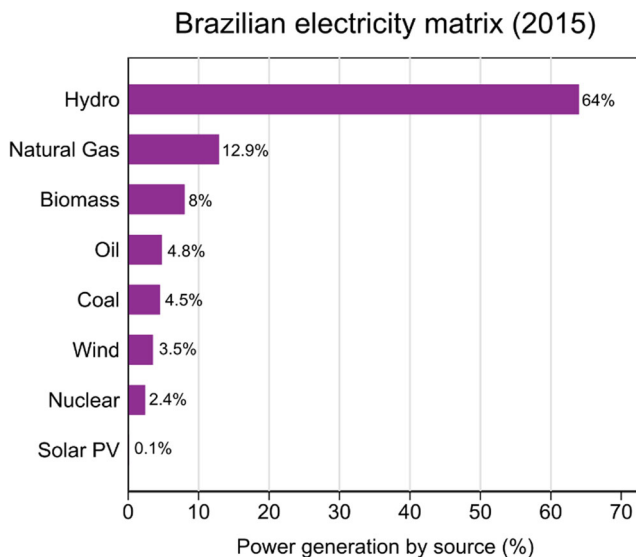
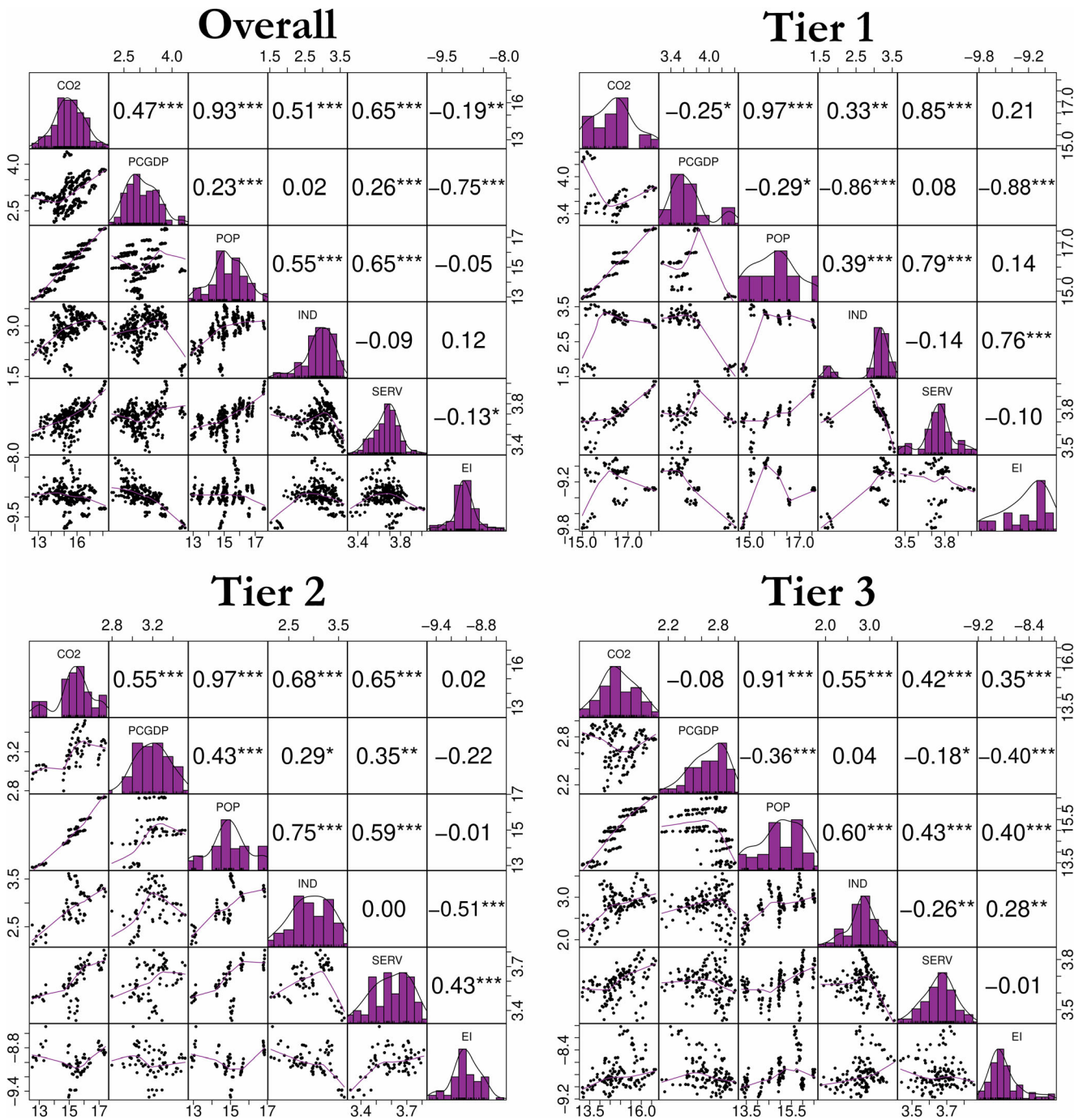**Fig. 6** Brazilian electricity matrix (base year 2015)

Fig. 7 Scatter plot (bottom), distribution (diagonal), and Pearson correlation coefficient (top) of each variable (in its natural-log form)

Table 8 Fixed-effects estimations and tests

Variables	(25) Overall	(26)	(27) Tier 1	(28)	(29) Tier 2	(30)	(31) Tier 3	(32)
PCGDP	1.239***	1.193***	1.352***	1.433***	0.835***	0.845***	1.471***	1.331***
	(0.0739)	(0.0706)	(0.128)	(0.119)	(0.139)	(0.143)	(0.112)	(0.109)
POP	2.707***	2.455***	2.487***	2.019***	2.821***	2.559***	2.554***	2.473***
	(0.148)	(0.145)	(0.274)	(0.283)	(0.324)	(0.320)	(0.223)	(0.214)
IND	−0.339***		−0.248**		−0.207*		−0.340***	
	(0.0544)		(0.121)		(0.121)		(0.0726)	
SERV		0.914***		0.967***		0.370		0.900***
		(0.116)		(0.233)		(0.304)		(0.154)
EI	0.0199	0.0868	0.733***	0.712***	0.000685	0.133	0.00614	0.0396
	(0.0746)	(0.0681)	(0.228)	(0.199)	(0.177)	(0.156)	(0.0939)	(0.0867)
Constant	−28.58***	−28.32***	−20.92***	−18.29***	−28.81***	−25.67***	−26.46***	−28.82***
	(2.531)	(2.430)	(5.495)	(5.058)	(5.821)	(5.534)	(3.559)	(3.445)
Hausman	68.63***	92.97***	39.26***	41.33***	29.43***	23.21***	43.14***	49.83***
Heteroskedasticity	94.67***	237.04***	8.66	9.76	106.34***	190.26***	49.45***	141.98***
Autocorrelation	5.185**	4.053*	33.114***	10.754**	0.132	0.062	20.865***	17.215***
Cross-sectional dependence	22.805***	21.453***	7.317***	8.397***	2.802***	2.101**	11.630***	9.166***
R^2	0.878	0.887	0.901	0.918	0.894	0.892	0.884	0.894
Observations	270	270	70	70	70	70	130	130
Number of regions	27	27	7	7	7	7	13	13

The standard errors are in parentheses

***$p < 0.01$; **$p < 0.0$; *$p < 0.1$

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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