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Research paper

Residential fuelwood consumption in Brazil: Environmental and social implications

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ABSTRACT

For a long time, firewood was the only source of energy available for cooking, heating, and protection. Currently, new forms of energy, such as liquefied petroleum gas (LPG) and electricity, have replaced the use of firewood. However, this fuel is still part of the energy matrix of many countries, including Brazil. Its use in cooking activities generates particles and gases that can have an impact on global warming and health. The objective of this study was to evaluate the use of firewood related to socioeconomic and environmental factors in Brazil. According to the results, firewood characteristics, per capita consumption, and distribution percentage vary widely within the country. Although LPG is the most used fuel in Brazil, a significant portion of the population - about 11 million households - still uses this fuel for domestic purposes, causing the highest emission rates of greenhouse gases. New research is necessary and may be the best investment to improve the quality of life and mitigate these climate change problems and health hazards.

1. Introduction

The World Health Organization (WHO) estimates that there are about 2.8 billion people dependent on solid fuels and rustic stoves for cooking and heating [1]. In general, burning of this type of fuel generates products of incomplete combustion (PICs) such as carbon monoxide (CO), methane (CH_4), nitrogen oxides, NO_x (NO and NO_2), sulfur oxides, SO_x (SO_2, SO_4^{2-}), organic compounds (benzene, formaldehyde, etc) and particles (black carbon, coarse, fine and ultrafine particles) with different chemical composition (e.g. polycyclic aromatic hydrocarbons (PAHs) and metals) [2]. Fine particles and domestic combustion emissions of coal and firewood are considered carcinogenic mixtures [3]. Exposure to PICs resulting from the burning of solid fuels has been responsible for the annual death of at least 4.3 million people around the world [1]. In addition, the gases and particles emitted by biomass combustion have direct and indirect effects on the climate [4,5]. Biomass combustion contributes significantly (20%–50%) to global greenhouse gas (GHG) emissions [6]. An important portion of biomass combustion occurs in rustic stoves, which are numerous around the world, and thus has the potential to contribute significantly to inventories of GHGs [7].

Many studies about the use of firewood as fuel have been performed, mainly in Asia and Africa. In many countries, the use of fuelwood is associated with fuel prices, seasonal influences, fuel availability, or cooking practices [8–10]. Some studies refer to the exchange of traditional stoves and fuels for cleaner ones [10–12], as well as energy supply from wood and other sources [10,13]; others discuss the cultural aspects that influence this use [13,14].

However, in Brazil, there are still few studies on the emission of gases and particles related to the use of firewood, stoves, and cooking methods, making it difficult to understand their effect on the health of the population and the environment. The use of firewood in the country varies because of climatic, socioeconomic, and cultural differences. In the South Region, cold and tradition induces the use of firewood, whereas in the North and Northeast Regions, the lower purchasing power of the population also results in the more frequent use of solid fuels. The few studies found in the literature show the prevalence of respiratory symptoms [15–18] and the incidence of cancer [19,20] related to biomass burning. Studies on firewood emissions [21,22], wood resources [23–25], and climate change [26,27] are scarce.

Based on the foregoing, the objective of this work was to evaluate the current status of the firewood use in Brazil using data from governmental agencies. The study aims to: 1) obtain the indices of production, consumption, and origin (silviculture or extractivism) of firewood; 2) estimate the per capita consumption of firewood; 3) evaluate the influence of economics on firewood consumption; and 4) identify the amount produced of three important greenhouse gases, namely carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and thereby obtain the GHG footprint of the major residential fuels.

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2. Materials and methods

2.1. Study area

Brazil is the largest country in the Latin American region, being the fifth largest in the world in territorial area, with about 190 million inhabitants, according to the latest census of 2010. The country is divided into five regions with different characteristics. The Midwest Region (or Central-West) is located between the biomes of the Cerrado and the Amazon forest and has advanced agriculture. Due mainly to the expansion of agroindustry, the destruction of these biomes has reached dramatic levels. The Northeast Region is marked by the semiarid climate, which hinders economic development through agriculture, resulting in a Human Development Index (HDI) lower than the national average. The primary vegetation of the Northeast is the Caatinga, a native tropical dry forest, which suffers from deforestation and misuse. In the North Region, socioeconomic development is related to the exploitation of the resources of the Brazilian Amazon. Agricultural and mining activities contribute to the generation of wealth, but also cause environmental degradation of large areas of forest. The South Region currently stands out in industrial and agricultural production and presents social indicators above the national average. The Southeast Region is the most industrialized and has the most urban centers, which consequently presents serious social problems due to the accelerated growth of the cities. The expansion of the cities was one of the factors that led to massive deforestation of the Atlantic Forest. Fig. S1 and Table S1 (Supplementary Material) present the Brazilian regions and their main characteristics.

2.2. Governmental data

In this study, data from two government agencies were used: 1) the Energy Research Company (Empresa de Pesquisa Energética, EPE), linked to the Ministry of Mines and Energy (MME), and 2) the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística, IBGE), linked to the Ministry of Planning, Budget and Management (MPBM).

Annually, the EPE publishes the Brazilian Energy Balance (Balanço Energético Nacional, BEN), which presents an accounting of energy supply and consumption, as well as the conversion processes and foreign trade. The IBGE, an agency founded in 1934, produces the country's current statistical and geoscientific information. The surveys provide data regarding Brazilian society, its population, economy, and living conditions, creating a complete picture of its evolution. Through these government databases, quantitative information was obtained on the use of firewood in Brazil for the most recent year available: 2016.

2.2.1. Firewood production

Information regarding firewood production, consumption, and origin will be derived from the reports of the Brazilian Energy Balance [28] and Production of Vegetable Extraction and Forestry (Produção da Extração Vegetal e da Silvicultura, PEVS) [29].

The EPE evaluates the residential consumption of the following fuels: natural gas, firewood, liquid petroleum gas (LPG), kerosene, gasworkers gas, electricity, and charcoal. Approximately eight hundred companies supply primary data about these fuels. The production of firewood and charcoal is based on consumption data and does not take into account any inventory variation [28]. In Brazil, charcoal (from wood) is used in all sectors, including residential. However, coal (fossil coal), transformed into metallurgical coal and steam coal, is not used for residential purposes, being mainly used in the electric generation and industry sectors [28]. Therefore, in this study, the term charcoal will be used. The PEVS report, published annually, provides information on the production of extractivism and forestry [29]. Extractivism considers the natural and spontaneous forest in each municipality and the products collected; forestry considers the existing forest, which has been planted and harvested by man, including the production of charcoal, firewood, and logs. The data are obtained by IBGE agents through interviews with public and private entities, producers, technicians, and other organizations linked to the sector [29].

2.2.2. Estimate of firewood per capita consumption

To estimate the firewood consumption per capita, the tons of firewood consumed in the residential sector (from BEN 2017 [28]) were used together with the number of households and the percentage of firewood users (from the National Household Sample Survey: Pesquisa Nacional por Amostra de Domicílios, PNAD [30]).

PNAD is a probabilistic sample household survey applied by IBGE agents. The survey investigates various socioeconomic characteristics of society, such as population, education, labor, income, housing, migration, health, etc. Currently, the annual PNAD has been replaced by the Quarterly National Continuous Household Sample Survey (PNAD continua), which provides more comprehensive territorial coverage and provides quarterly information on the workforce nationwide. Until 2015, PNAD questioned the populace: “The stove of this household uses predominantly: a) LPG, b) gasworks gas, c) firewood, d) charcoal, e) electricity, f) others.” With this question, only one fuel could be chosen. From 2016, the question was changed to: “Which fuel(s) are used in this household in the preparation of food? a) LPG or gasworks gas, b) firewood or charcoal, c) electricity, d) others.” With this update, the PNAD now allows the choice of more than one fuel used for cooking.

The firewood consumption per capita by year was calculated as followed:

Consumption per capita (kg/person/year) = consumption/[households x firewood users x 3]

Where:

Consumption = firewood consumption (kg/year) in 2016 in the residential sector [28]
Households = total number of domiciles in 2016 [30]
Firewood users = percentage of firewood users in 2016 [30]
3 = the number of people in each household

2.2.3. Estimate of greenhouse gas emissions from the burning of cooking fuels

The Kyoto Protocol, and more recently the Paris Agreement, seeks to reduce emissions of GHGs from anthropogenic sources. The gases considered in the protocols are CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs); perfluorocarbons (PFCs); and sulfur hexafluoride (SF_6) [6]. To evaluate the impact of a given product on global warming, the measure known as the Global Warming Potential (GWP) is adopted [6]. The GWP of a gas is the impact it causes on global warming relative to an equivalent unit of carbon dioxide (CO_2e) over a given period of time (usually 20, 100, or 500 years) [6]. GWP negative values indicate net reductions in potential atmospheric heat retention, and positive values indicate net increases in the potential for atmospheric heat retention. By definition, CO_2 is assigned a GWP of 1 for any unit of time [31].

To estimate GHG emissions from fuels used in cooking in the country, data from the latest BEN [28] were used, as well as the calculations suggested by the Intergovernmental Panel on Climate Change [31,32] and the Brazilian protocol [33]. The Tier 1 method from IPCC was chosen to calculate the emissions. Tier 1 is the simplest method that uses the default data provided by the IPCC, which allow estimates to be made by any country [32]. The equation is:

Emissions tCO_2e = fuel consumption x emission factor x GWP of gas

where:

Emissions tCO_2e - emissions of a given GHG by type of fuel in tons of

CO_2 equivalent

Fuel consumption - amount of fuel combusted (TJ). Residential consumption of fuel registered in Brazil in 2016 was: LPG ($10,758 \times 10^6\,m^3 = 271,747$ TJ), firewood ($19,561 \times 10^6\,t = 253,902$ TJ), charcoal ($6,64 \times 10^5\,t = 17,961$ TJ), natural gas ($4,05 \times 10^8\,m^3 = 14,920$ TJ) and kerosene ($3,0 \times 10^3\,m^3 = 103$ TJ) [28].

Emission factor - default emission factor of a given GHG by type of fuel (t gas TJ^{-1}) [32].

GWP = global warming potential for each gas with the following values updated in 2013 [31]: for a 20-year time horizon: 1 for CO_2, 84 for CH_4, and 264 for N_2O; for a 100-year time horizon: 1 for CO_2, 28 for CH_4, and 265 for N_2O.

The conversion factors are presented in Table S2 (Supplementary Material).

3. Results and discussion

3.1. Firewood production

The EPE divides the use of firewood by sectors: residential, industrial, agriculture and transformation [28]. Firewood is considered from two origins: "picking firewood" (free firewood), originated from branches and trunks (dry) of native forests, isolated trees and collected on properties or along highways; and firewood produced for commercial purposes, which comes from native forests, currently replaced by reforestation wood, with eucalyptus being the main species cultivated for this purpose [29]. Brazil has no need to import firewood, producing the entirety of what is consumed. In 2016, the production of firewood (free picked + commercial) was 7.45×10^7 t, being 1.96×10^7 t (26.5%) consumed by the residential sector with different purposes (cooking, heating, lighting, etc.). These rates have remained stable over the last 5 years.

IBGE classifies firewood as coming from forestry (silviculture) or from extractivism. In 2016, $2.5 \times 10^7\,m^3$ of firewood from the extractive sector and $5.3 \times 10^7\,m^3$ from forestry were produced, totaling $7.8 \times 10^7\,m^3$. According to the latest survey, the Northeast Region is the most dependent on extractive firewood ($1.5 \times 10^7\,m^3$, 62% of the total), while the South is the most dependent on forestry ($3.4 \times 10^7\,m^3$, 64% of the total) (Fig. 1) [29]. As expected, in the North and Midwest regions, timber predominates in both the forestry and extractivism sectors because these regions are located in the Amazon forest. In the context of Brazil, forestry predominates over extractivism, but firewood stands out as the main product of the latter. In 2016, charcoal, firewood, and timber from extractivism decreased compared to 2015, around 31.7%, 7.4%, and 7.0%, respectively [29]. According to the IBGE, the reduction is due to lower consumption by the steel industry, the gradual replacement of the product with other energy sources, and better supervision in avoiding illegal commerce.

Exclusive users of firewood are concentrated in the poorest regions of the country, such as in the Northeast Region (states of Bahia, Pernambuco, Ceará, Maranhão, and Piauí) and in the semi-arid region of northern Minas Gerais [34]. In these regions, a considerable amount of firewood is removed in a non-sustainable way [34–40]. The Caatinga, the characteristic vegetation of the Norhtwest, is the biome that has been most degraded with the illegal exploitation of firewood both for residential and industrial purposes [41]. This vegetation has been reduced to less than half of its original area [26], resulting in desertification in many areas [35,41,42,43]. The unsustainable exploitation of firewood in this region is related to the purchasing power of the population, which is one of the lowest in the country. While firewood is obtained at no cost in the local forests, other forms of energy are considered expensive by the population. Studies have shown a direct relationship between population growth, the Human Development Index (HDI), and deforestation rates [44,45].

The lack of technical criteria in timber harvesting, illegal logging, poor monitoring, lack of monitoring, and corruption has accelerated the destruction of forests, soil, and ecosystems in vulnerable regions [42,43,46,47]. To minimize deforestation in impacted regions, such as the Caatinga, the Ministry of the Environment has created openings for managers of firewood production [48]. Some funds (e.g., the National Forest Development Fund and the National Climate Change Fund) are intended to help farmers and industries in the Caatinga region achieve sustainability of the fuelwood and charcoal chain in the NE [48].

3.2. Residential use of firewood

The EPE's estimate for 2016 indicated three sources of residential energy used for different purposes: electricity (46.0%), LPG (26.5%), and firewood (24.4%) [28]. Other sources represented little in the residential energy matrix: charcoal (1.7%), natural gas (1.4%), kerosene, and gasworks gas (0.0%).

The PNAD survey asked specifically about the main fuel used in cooking until 2015. Considering only the valid data, and excluding the missing and not applicable data, the PNAD results showed that the fuels most used in households for cooking were LPG (93.2%), firewood (3.2%), gasworks gas (2.9%), charcoal (0.71%), electricity (0.05%), and others (0.004%), totalizing 100%. In 2016, the PNAD offered more than one option to indicate which fuel was used for cooking. In this survey, LPG was the most used (98.4%), followed by electricity (32%) and firewood + charcoal (16.1%); other fuels (e.g., kerosene, biogas, natural gas, etc.) had insignificant indices (0.1–0.2%) [30]. The sum of all percentage fuels totals about 147%, meaning firewood + charcoal and electricity are not used exclusively, but rather shared with other fuels, mainly LPG.

Studies performed in different regions show higher percentages than those presented by both IBGE and EPE. According to the Ministry of the Environment, it is estimated that 85% of the rural families in the Northeast use firewood [49]. On-site studies the percentages of the predominant use of firewood ranges from 17 to 87% [36,37,50]. In addition, a significantly high percentage of households uses both firewood and LPG (60–90%) [37,50].

3.3. Firewood consumption per capita

In 2016, $19,561 \times 10^6$ kg of firewood and 664×10^6 kg of charcoal, both derived from plants, were consumed by the residential sector without being specifically for cooking [28]. According to the last PNAD, in 2016 there were 69,223,575 households, of which 16.1% used firewood + charcoal to cook (Table 1) [30], corresponding to 11,144,996 domiciles. Each domicile is composed of an average of 3 inhabitants, therefore, 33,434,987 individuals consumed in 2016 about 605 kg of firewood per person (1.7 kg/person/day). Traditionally, firewood has been the most important source of biomass in developing countries, with an average per capita estimate of 700 kg/year (1.9 kg/person/day) [51], which is similar to that estimated in this study. However, in other Brazilian studies, higher consumptions were estimated (1000–1008 kg/person/year), but with fewer inhabitants (25–30 million people) [52,53]. The per capita differences among studies are probably due to the lower consumption of firewood and the population increase in recent years. Uhlig (2008) [34] used the Institute of Electrotechnical and Energy (IEE) method to estimate the consumption of firewood and charcoal in Brazil from 1996 to 2005. The results showed that in the residential sector the consumption of firewood was about half of the value provided in the BEN. The differences in firewood and charcoal consumption values are due to the criteria used for estimation by MME and IEE. MME uses correlations with LPG that consider certain stability in the amount of useful energy needed for cooking a family's food. The specific consumption used was 17.5 m^3st/household/year for the exclusive consumer of firewood and 9.7 m^3st/household/year for consumers of firewood and LPG. According to the IBGE study, however, the

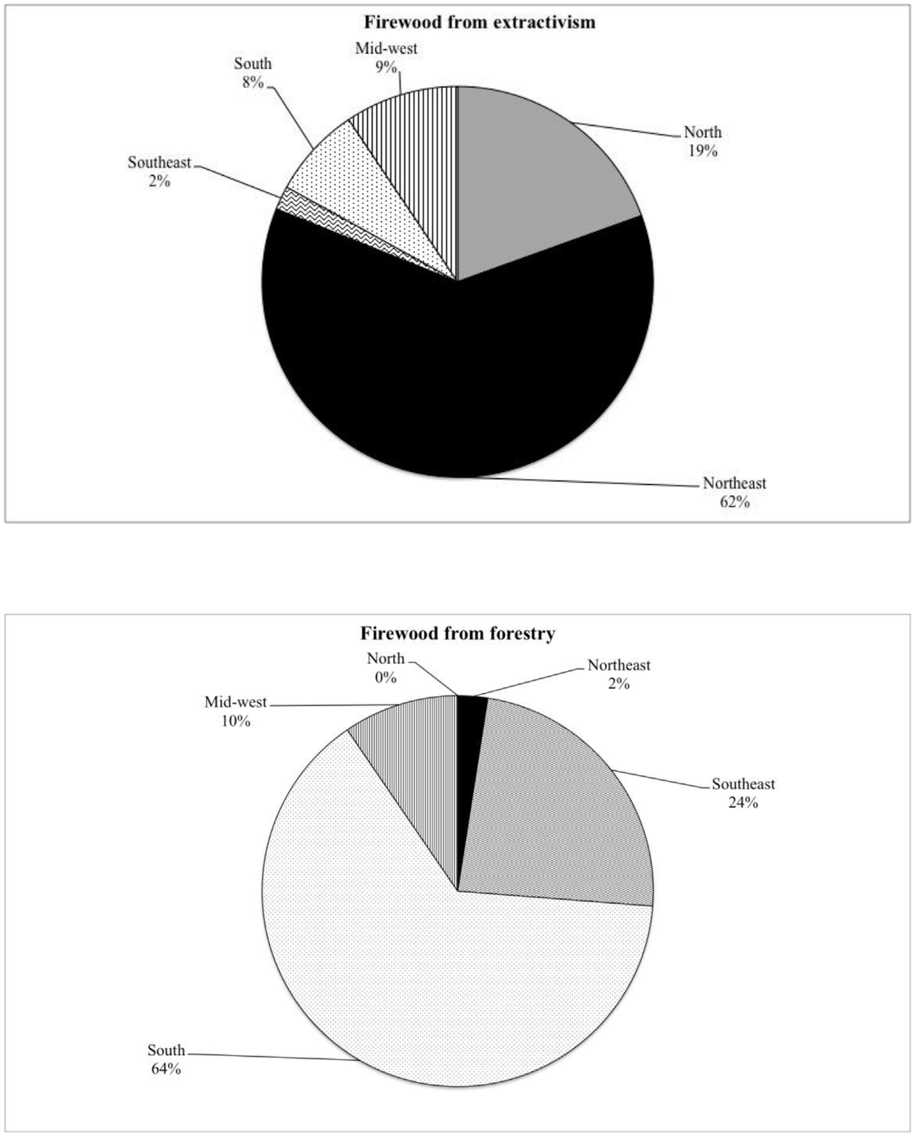

Fig. 1. Percent production profile (in m^3) of firewood from forestry and extractivism by region in 2016.
Source: IBGE [29].

IEE estimated the consumption of firewood and charcoal with consideration of the number of stoves per type of fuel. The specific consumption by exclusive consumers of firewood in rural areas was 7.7 m^3st/household/year and 6.8 m^3st/household/year for consumers of both firewood and LPG.

On-site studies, which basically track "free firewood", show variations from one place to another, and also differ from national statistics. Studies carried out in different years in several regions estimated that consumption varied from 0.7 kg/person/day to 8.5 kg/person/day [38,54]. The differences in consumption are related to the availability and quality of firewood, use of other types of stoves (e.g., LPG), stove efficiency, and the socioeconomic, geographic, and climatic characteristics of each region.

Table 1
Fuel used in cooking and number of domiciles in Brazil and by region.

	Brazil		North		Northeast		Southeast		South		Midwest	
Fuel used in cooking	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Total households (million)	69,224	69,773	5003	5125	18,321	18,453	30,152	30,230	10,482	10,582	5266	5383
LPG (%)	98.4	98.4	98.0	97.8	97.1	96.8	98.9	99.1	98.7	98.8	99.4	99.0
(Household – million)	(68,116)	(68,657)	(4902)	(5012)	(17,790)	(17,862)	(29,820)	(29,958)	(10,346)	(10,455)	(5234)	(5329)
Firewood + charcoal (%)	16.1	17.6	29.5	33.5	22.1	24.1	6.1 (1839)	6.9 (2086)	25.2	26.7	21.3	22.9
(Household – million)	(11,145)	(12,280)	(1476)	(1717)	(4049)	(4447)			(2641)	(2825)	(1122)	(1232)
Electricity (%)	32.0	39.2	19.5	31.6	16.7	20.8	32.9	42.7	53.9	58.2	48.4	52.3
(Household – million)	(22,152)	(27,351)	(975)	(1581)	(3060)	(3746)	(9920)	(12,908)	(5650)	(6160)	(2549)	(2815)
Others (%)	–	–	0.1	0.2	–	0.1	–	–	–	–	–	–
(Household – million)												

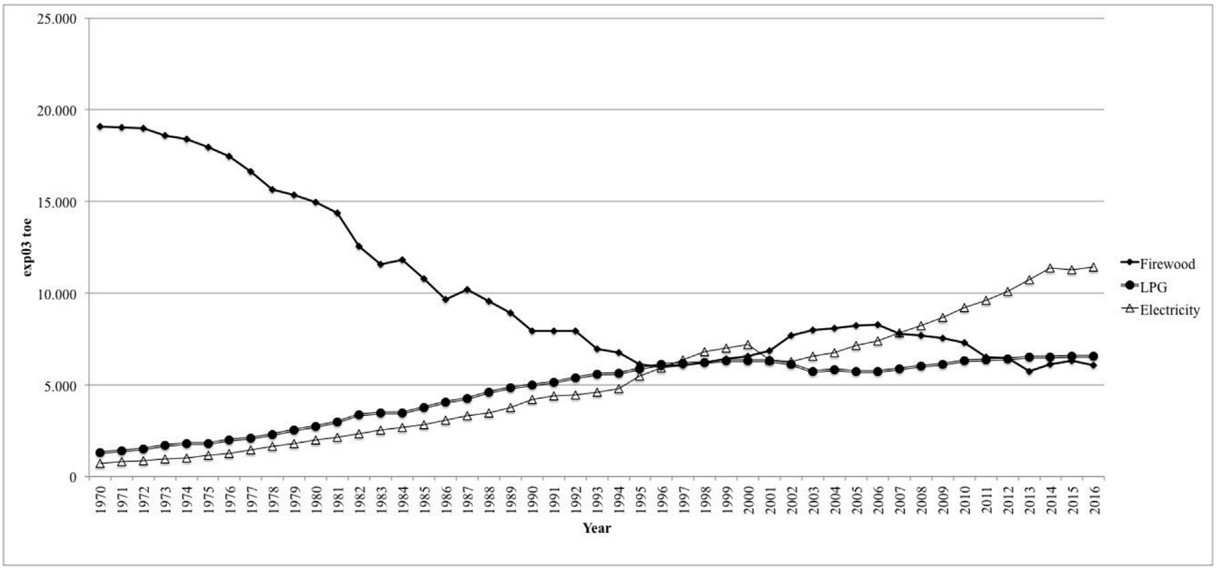

Fig. 2. Trend in the use of firewood, LPG, and electricity for residential purposes.
Source: EPE [28].

3.4. Impact of the economic factor on the use of firewood

Firewood has played a major role in the Brazilian energy matrix since colonial times when it was used in boilers and stoves [42]. The historical series, started from 1970, shows the profile of firewood used in the country (Fig. 2) [28]. Average consumption in the 1970s was 18,000 toe, dropping to 6800 toe in the 1990s, resulting in a reduction of 60%. From the 1990s, the consumption has remained stable: approximately 7000 toe. This reduction is related to the migration of the population to the cities, where other forms of energy (such as electricity and LPG) are available. This decrease in firewood consumption is proportional to the increase in LPG and electricity use (Fig. 2). The Brazilian LPG program started in 1930 and has been decisive in reducing the use of firewood. Presently, it is estimated that more than 70% of LPG is destined for the residential sector. For the most part, the insertion of this fuel into the domestic sector is due to several factors, like efficient regulations, good commercial practices, subsidies, and government assistance programs.

From 1973 to 2000, LPG received subsidies of 18% and the sale price for 13 kg cylinders was the same in all regions. In May 2001, the lack of subsidies resulted in higher prices, reduced consumption, and migration to other alternative fuels (Fig. 2). In the same year, the "Gas Assistance" ("Auxílio-Gás" or "Vale Gás") program was created. It is a government assistance program that has influenced the use of LPG as a substitution for firewood. This program transferred subsidies for the purchase of residential LPG to families who received less than half of the minimum wage. In 2003, Gas Assistance was included in the "Family Allowance" ("Bolsa Família"). However, this inclusion has not been very effective in reducing the consumption of firewood since low-income families who receive the benefit often spend it on food and other items.

According to the latest PNAD [30], in 2017 more families (17.6%) used firewood as fuel for cooking compared to 2016 (16.1%) (Table 1). However, LPG consumption remained stable in those two years (98.4%). It is important to note that the number of domiciles in the country increased by 0.8% compared to 2016, which causes some differences in the indices. Overall, these results indicate that firewood and charcoal have not replaced LPG but are being used as auxiliary fuel. However, evaluating the South-Southeast and Northeast Regions, different behaviors can be observed. The Northeast presented the highest increase in firewood + charcoal consumption, reaching 398,000 households (Table 1). Since this region hosts a low-income population, the growth of firewood or charcoal users likely indicates an exchange for cheaper fuel. The increase of users in this region may be directly related to prices, since, in June 2017, Petrobras changed its policy and began to follow international prices. Between June 2016 and 2018, the average price of the 13 kg cylinder increased by around 26%, well above the country's inflation rate (8%).

The South and Southeast regions, however, had a slight increase in both firewood and LPG consumption. Historically and culturally, the wood stove has always stood out in these regions, mainly in the winter, to provide a place of warmth for gathering and cooking. It is also a tradition to have wood grills and fireplaces in most of these houses. Since these are high-income regions, other factors, such as decoration and style, influence stove acquisition. In this case, the stoves are of good quality and the firewood is usually obtained from legal trade.

Charcoal consumption is related to an important cultural habit spread in the country at all income levels: the barbecue ("churrasco"). This charcoal is sold in bags in the supermarket and can be considered sustainable due to the origin of the wood, predominantly forestry, and the low consumption per household (6.8 kg/month) [34].

The 2017 PNAD does not provide data on social stratification; therefore, it is not possible to evaluate the influence of LPG prices on the increase of firewood users. However, several studies indicate that the use of firewood is related to the price of other fuels (LPG and electricity) [27,36,46,51]. Informal surveys carried out by the media have also shown an increase in families that use firewood due to the increase in LPG prices. In low-income communities, the search for "picking firewood" in many of these cases results in accidents and loss of time to carry out other activities. Additionally, an improvised wood stove is used in many houses, which has been increasing the number of residential fires and burn injuries. Another factor in the increase in firewood consumption was the trucker strike in May 2018: trucking is the main means of transport for LPG. This strike resulted in increased consumption of firewood for months due to two factors: the LPG trade was depleted and prices, due to scarcity, increased significantly, directly affecting the poorest population.

The energy required for cooking represents an important cost for low-income families. According to a non-governmental survey, two-thirds of the Brazilian population believes that the growth of LPG compromises the family budget. The lower the income, the higher the percentage of the family budget that must go toward the purchase of LPG. For example, if a family receives "Bolsa Familia," the LPG cost represents about 37% of the domestic budget; if it receives one

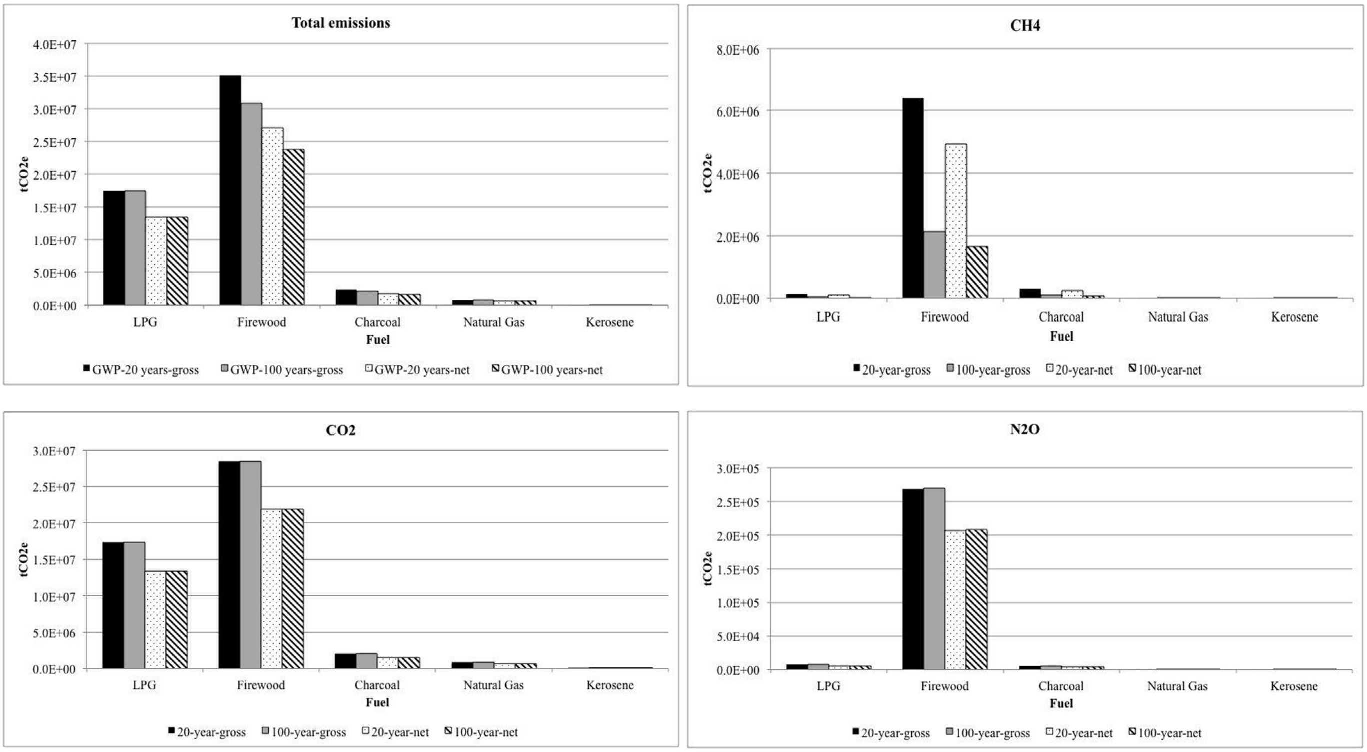

Fig. 3. Estimation of emission rates of the main greenhouse gases (CO_2, CH_4 and N_2O), in tCO_2e, due to cooking in Brazil in 2016, considering two sceneries (20-year time horizon and 100-year time horizon) and net and gross emissions.

minimum wage it represents 7%, and if it receives 10 minimum wages it represents 0.7%. The rise in the price of LPG added to the current economic crisis, which reduced income, shrank purchasing power, and increased unemployment, leading to reduced use.

There is no doubt of the necessity to provide a financial incentive for the acquisition of cooking fuel to the low-income population since nutrition problems occur when they cannot afford to buy LPG regularly for food preparation. A subsidy may be an alternative, but it should not be paid for by the fuel companies since it could result in the loss of capital, leading to irreversible damages. It is necessary to discuss an alternative. One option would be to return to the "Vale Gás," where this subsidy is only allowed to be used for LPG. A more viable alternative is long-term planning to make LPG cheaper. In that regard, investments in LPG refinement could develop a more competitive domestic market and be less dependent on the foreign one. A third option would be alternative fuel, such as gasworks gas, biogas, solar energy, etc., to avoid dependence on only one fuel type. Encouraging the use of sustainable firewood and efficient stoves is also a consideration.

The use of solid fuels (e.g., firewood, coal, crop residues, etc.) is directly related to the level of development of a country; thus, it is directly related to impoverished populations who are already deprived of a good public health system in general, which makes the situation even more serious. In a study performed with 150 countries, a non-parametric model was used to estimate the percentage of families that depend on solid fuel [55]. According to the results, the average rate of use of solid fuels was quite high, accounting for 41% of the total energy used worldwide, mainly for cooking [55]. Industrialized (high-income) countries use less than 5%, while in poorer regions, e.g., Sub-Saharan Africa, Southeast Asia, and the Western Pacific Region, the percentage may reach 95%. Although the proportion of households using solid fuels as primary fuel for cooking declined in all regions between 1980 (62%) and 2010 (41%), the number of people exposed to domestic pollution remained stable at approximately 2.8 billion [55]. Among several countries in Africa, Asia, and Latin America, Brazil was the country that presented the highest consumption of LPG (97.6%) for cooking and one of the only ones to use crop residues, animal manure, kerosene, and electricity for this purpose.

3.5. Emission of greenhouse gases generated by the residential sector in Brazil

There is a large range of particles and compounds emitted during incomplete biomass burning that affect the climate. However, analysis of all these pollutants is a difficult and often impossible task. In addition, there are many uncertainties about the global warming potential of many products of incomplete combustion [56]. In order to compare the benefits of a given fuel to another in terms of global warming, it is important to define which by-products of combustion are being considered. In general, the gases present in the Kyoto Protocol used for biomass burning are CO_2, N_2O, and CH_4, although many others have direct and indirect effects on global warming, such as black carbon [56]. If CO_2 comes from the renewable harvesting of biomass, its emissions have no net increase in GWP, but if CO_2 comes from non-renewable harvesting, its behavior is similar to fossil fuels [56]. If the combustion is inefficient, as occurs in most household stoves, firewood is converted into PICs, products that have a greater climatic impact than CO_2 [56]. Overall, CO_2 from biomass combustion is considered to be carbon neutral, especially when it is sustainably produced [57,58]. Some researchers disagree and advise that CO_2 should always be considered in emissions [59,60]. CO_2 was included in this study since most of the fuelwood in question does not come from renewable sources and thus impact global warming.

Based on the emission factors presented by the IPCC [32] and the consumption of each fuel used by Brazilian families according to the latest BEN [28], the 2016 GHG emission rates of CO_2, N_2O, and CH_4 were calculated considering 20-year and 100-year time horizon global warming potentials (Fig. 3). The results show that the firewood (2.5 x 10^5 TJ) and LPG (2.7 x 10^5 TJ) consumptions were similar in 2016. However, the CO_2e emissions for the three GHGs were two times higher for firewood than for LPG in both scenarios. This occurs because of the high quantities of CH_4 and N_2O emissions generated from fuelwood. Similar results were observed in India, where fuelwood had the same emissions as LPG and kerosene due to high CH_4 and N_2O emissions [61].

Comparing the two scenarios, 20-year and 100-year, there is a clear difference between firewood and charcoal behavior compared to other fuels (Fig. 3). These fuels' impact on global warming is greater in the short term than in the long term due to the shorter lifespan of CH_4. The lifetime of methane is about 12 years, whereas the lifetime of N_2O is 120 years. The shorter the lifespan, the greater the influence the gas will have on global warming in the short term. Therefore, for CH_4, the 100-year GWP (28) is much less than the 20-year GWP (84). In this way, the impact of CH_4 is three times higher in a 20-year time horizon than in a 100-year time horizon. Although the N_2O does not show a difference between the two scenarios, the impact is much higher for firewood than for LPG and other fuels due to higher emission factors.

Coelho et al. [27], using data from the 2012 BEN, found similar results to this study. The firewood and LPG consumption were also similar, and the CO_2e emissions of the firewood were two times higher than the LPG. In other words, the GHG emissions profile has remained constant in recent years, and the high emission of carbon in Brazilian households continues to be caused by firewood.

According to the Climate Observatory (a civil society network with the objective of discussing climate change in Brazil), in 2016 the gross emissions by all sectors in Brazil were estimated at 2.3 x 10^9 tCO_2e, representing 3.4% of the world, being the 7th largest polluter on the planet [62]. GHG emissions from fuel combustion were 4.0 x 10^8 tCO_2e, representing 18% of the total gross emissions. In this context, the emissions from residential sources represented 2% of Brazil's gross emissions and 13% of emissions from fuel combustion. A total net emission, in which the carbon is removed from the atmosphere by human actions such as the restoration of forests, was also estimated. In Brazil, anthropogenic CO_2 removals are related to areas of environmental protection (AEPs) and indigenous lands (ILs). A removal factor is estimated and multiplied by the forest area in AEPs and ILs. The result is a deflation that can reach hundreds of millions of tons of CO_2e in national emission inventories. Brazilian technicians consider this approach problematic since there is no guarantee that forests in these protected areas, mostly mature tropical forests, are removing carbon in that amount [62]. For this reason, gross emissions are more commonly used. The net emissions for 2016 were estimated as 1.75 x 10^9 tCO_2e, which is 23% lower than gross emissions. Fig. 3 compares both scenarios.

The GHG emissions from the residential sector in India were 1.1 x 10^8 tCO_2e [61]; while in Indonesia it was 2.92x10^8 tCO_2e [63]; and Chinese biomass burning emissions were 9.94x10^8 t for CO_2e, 90% of which were the result of firewood use, crop residues being burned as fuel, and crop residues being burned in field burnings [64]. These emissions are much higher than found in this study (5.1–5.6 x 10^7 tCO_2e).

Bhattacharya and Salam (2002) [57] estimated GHG emissions in different countries of Asia (China, India, Nepal, Pakistan, the Philippines, Sri Lanka, and Vietnam) for different stoves and fuels (firewood, natural gas, kerosene, and LPG). Total GHG emissions by year ranged from 1.0 x 10^6 to 3.0 x 10^7 tCO_2e for traditional firewood stoves; 1.6 x 10^6 to 5.5 x 10^7 tCO_2e for natural gas stoves; 1.9 x 10^6 to 6.5 x 10^7 tCO_2e for LPG stoves; and 3.4 x 10^6 to 1.2 x 10^8 tCO_2e for kerosene stoves. Permadi et al. (2017) [63] developed a similar study in Indonesia. Estimates of GHGs for residential emissions were 2.1 x 10^8 tCO_2e for firewood, 6.3 x 10^6 tCO_2e for kerosene, 1.1 x 10^7 tCO_2e for LPG, and 6.1x10^7 tCO_2e for charcoal [63]. In the present study, the GHG emissions were 3.1 x 10^7 tCO_2e for firewood, 7.5 x 10^3 tCO_2e for kerosene, 1.7 x 10^7 tCO_2e for LPG, 2.1 x 10^6 tCO_2e for charcoal, and 8.4 x 10^5 tCO_2e for natural gas. The GHG emission rates from the Brazilian residential energy matrix were lower than those of the Asian countries. However, due to differences in calculation methodology, characteristics of the stoves, and emission factors, among other things, this direct comparison is only informative. Additionally, data on wood fuels are often from secondary sources, making it difficult to compare across countries. To move forward with real and reliable data collection, trained staff and significant financial resources are required.

4. Conclusions

Firewood in Brazil continues to be an important fuel in the energy matrix, although its consumption has been decreasing since the 1970s. Variation in firewood production and consumption has been small in recent decades, indicating that the current rate is stable and should be considered in future studies. The use of firewood is driven by purchasing power, availability, and cultural use.

In economic terms, the use of firewood by the low-income population seems to be directly associated with the price of LPG. In general, the firewood used by this population is of "picking" quality (gathered from the land without cost) and the stoves are rustic. These characteristics increase the risks of accidents and health and environmental problems. It is necessary to develop public policies that favor access to cleaner and cheaper energy for the poorest population. Some alternatives are investments in the areas of LPG extraction and production, a specific government program for energy purchase, or the implementation of alternative energies, such as solar, wind, and biogas or sustainable biomass, taking advantage of the country's great forestry potential. However, it is necessary to carry out an in-depth study, since all the alternatives have their own advantages and disadvantages. For the richest class, the increase in consumption of firewood is due to other factors, such as the improvement of kitchens and balconies and new models of stoves and grills.

Concerning the environmental impact, the use of firewood has led to the increase of deforested areas in some regions. The Northeast Region has a very dry climate, which causes the land to be unproductive, resulting in the impoverishment of the local population. In this way, local ecosystems, such as the Caatinga, are exploited in an unsustainable way to obtain, mainly, energy (firewood) in both the residential and commercial sectors. To minimize these impacts, in this and in other deforested regions, educational programs and sustainable management must be the tools used by the governments. Regarding global warming, firewood was the fuel with the highest GHG emission rate. Considering that firewood is a neutral carbon, its use must be associated with reforestation biomass and more efficient wood stoves (reduce heating costs and emissions). In this way, the effects of GHG emissions would be minimized as would indoor pollution. The use of improved cook stoves and clean fuels (e.g., LPG, biogas, solar cooking, and alcohol fuels) will result in high fuel efficiency and low pollution emissions.

Regarding governmental data, all firewood and charcoal consumption analyses performed were based on the official information currently available and produced by the EPE and IBGE. The research carried out by the EPE and IBGE has some limitations, although they follow adequate protocols that make their data reliable. These differences are more evident when compared with in situ studies. There are uncertainties about the current consumption of firewood in the residential sector, mainly due to lack of information. Because a significant portion of this fuel is not marketed, and the primary data collection costs are high, the available data comes from estimates or secondary data, inducing errors. In addition, to estimate firewood consumption, the EPE uses 40-year-old methods, the details of which are only technical notes. The method for evaluation of residential firewood use is correlated with LPG, which presents relevant problems and lack of precision. For example, the reduction of LPG consumption due to substitution by other sources of energy (e.g., natural gas and electricity) and better stove efficiencies could be erroneously interpreted as causing an increase in the share of firewood consumption in households.

To obtain more reliable data, a survey needs to be administered in all households with specific questions that address topics such as fuels used in this house, frequency of use, consumption, type of stove, location of stove (indoor or outdoor), family income, source of firewood or charcoal (picking or commercial), and if there are symptoms of related health issues, etc.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2018.11.014.

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