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REGULAR ARTICLE

# Study of GHG emissions in Brazil from 1990 to 2030 using system dynamics for simulation

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## Abstract

This work studied five sectors which are responsible for GHG emissions in Brazil, namely: Agriculture, Energy, Land-use Change, Industrial Processes, and Waste. In addition to emissions, the Brazilian National Energy Balance was studied to understand the relationship between the energy matrix and GHG emissions. This entire study was developed using the System Dynamics methodology and, at the end, two scenarios were proposed. In the first scenario, it is possible to observe how GHG emissions are distributed in Brazil, while in the second scenario, it is possible to observe a reduction of about 48.9% of emissions in the country, related to the reduction of Land-use Change and Forestry together with the Energy Sector.

## Keywords

System Dynamics; GHG emissions in Brazil; Renewable energy; Energy matrix; Simulation.



## Introduction

Greenhouse Gas (GHG) emissions have increased every year, as developing countries need to use more energy to produce and prosper. GHG emissions on a large scale is a source of concern all over the world. One of its effects is the increase in terrestrial temperature, heavily intensifying and influencing Climate Change worldwide (Adger; coauthors including Fischlin, 2007).

Governments around the world have come together and created organizations like the Climate Summit that aim to find a solution to the looming problem. It was stipulated that its member countries should adopt measures to reduce greenhouse gas emissions. Among these measures, it was decided that, in the year of 2020, emissions should be the same as they had been back in 1990 ("United Nations Climate Action Summit 2019", 2019).

In view of this information, the present work aimed to study greenhouse gas emissions in Brazil starting from the year of 1990 to 2030, through simulation, using System Dynamics (SD). This simulation technique was chosen because it allows relating several variables and seeing how each one contributes to the emission of polluting gases.

The general problem here is related to which sectors are responsible for GHG emissions in Brazil and how each one contributes to increase or reduce these emissions. Some hypotheses may also be raised, such as: the Land-use Change and Forestry sector should have a significant contribution to emissions, and the Energy sector should also have a significant participation in the increase in GHG, due to the energy matrix being composed of more than 50% of non-renewable energy. The question that arises in view of these issues is: will Brazil be able to reach the goal of reducing GHG emissions to the same values of 1990 by the year of 2030?

GHG emissions in Brazil grow every year. In 2010 for example, $CO_2$ emissions were largely produced by agriculture and land use caused by deforestation. Deforestation occurs mainly in the Amazon Forest region, an area rich in flora and fauna and that has been deforested to make way for pastures and planting for agriculture. The Brazilian government has been monitoring these areas to inhibit and contain illegal fires and deforestation, and if someday these issues are under control, then, the Energy sector will become the main source of GHG emissions in the country (Lucena et al., 2014).

In this regard, Brazil has an interesting energy matrix, since it was only in 2013 that its primary energy source (40%) was a source of the renewable energy category. Besides, due to the country profile and natural resources, this number (40%) can increase with government incentives. This way, the study of GHG emissions is important for society as a whole, because

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it allows us to understand how each country contributes to reducing $CO_2$ on the planet (Lucena et al., 2014).

Therefore, this work's general objective is to analyse GHG emissions in Brazil using System Dynamics for scenario simulation. More specifically, this article aims to identify GHG emissions in Brazil according to each sector, starting from the year of 1990 to 2020; carry out the Brazilian annual energy balance from 1990 to 2020; build a simulation model for GHG emissions in Brazil; and finally, propose and analyse two possible scenarios for GHG emissions in the country.

### *Climate Change*

Climate Change is not a recent phenomenon to Planet Earth, since it was perceived by both man and other living beings that have been part of this ecosystem for approximately the last 200 years. Nevertheless, in the last 50 years, human activities specifically have caused the Earth's temperature to increase by an average of 0.750 C. This increase in temperature has brought about climatic changes that can be observed and measured, such as rising sea levels, an increase in the period of droughts, torrential rains, an increase in the number of tropical cyclones, melting of the polar layers, among others (Ashrafuzzaman; Furini, 2019).

Many cities are located in coastal regions, such as Rio de Janeiro in Brazil, Cape Town in South Africa, Cinque Terre in Italy, among others. These areas are prone to flooding risks caused by Climate Change, which leads the sea levels to rise and coastal cities and populations to be exposed to coastal disasters (Baills; Garcin; Bulteau, 2019).

### *Greenhouse Gas Emissions*

The impacts caused by global warming are classified in $CO_{2eq}$ and divided into three groups: The first group concentrates GHG emissions that occur in waste treatment facilities and their operations. The second group concentrates indirect emissions, that is, those outside waste treatment. The third group is comprised by the impacts of GHG emissions that were interrupted due to the reuse of materials and energy recovered or recycled within the system. The concept of Global Warming Potential (GWP) was developed by the Intergovernmental Panel on Climate Change (IPCC) in order to generate comparisons of each GHG ability to retain heat in the atmosphere, when compared to other gases (Maria; Góis; Leitão, 2019).

In 1975, Brazil instituted the National Alcohol Program (Proálcool) which was an initiative to reduce dependence on fossil fuels, which would generate a reduction in GHG in the country. Ethanol is produced from sugar cane and has been used as a fuel in total or partial replacement in the Brazilian vehicle fleet. It is considered a sustainable fuel because it reduces pollution and minimizes Climate Change, so national cars that use a mixture of gasoline and ethanol with up to 26% (dehydrated ethanol) are known as flex-fuel cars (Zang; Martins; da Fonseca-Zang, 2018).

With population growth, improvements in industrialization, and income growth, the demand for energy, food, and drinking water is increasing. As a result of this, Climate Change is increasingly recurrent, as is the case in Brazil, among many other developing countries. At first, it seems just a problem of resource management by the Brazilian government, but the issue is more complex. This complexity is due to the fact that Brazil is one of the countries that can be most significantly affected by Climate Change. On the other hand, it is also a country whose economy is linked to the export of agricultural commodities and energy, meaning that the impacts upon Brazil can have consequences for the rest in the world (Mercure et al., 2019).

### *GHG Emissions in the Agriculture Sector*

Population growth demands an increase in food production, and it is estimated that, in the coming years, there will be an increase in land destined for cultivation or pasture so that it can meet these new demands. In recent years, investments have been made in fertilizers, advances in genetics, and improved livestock food to increase breeding. However, despite these investments, this sector's GHG emissions and water consumption increased, as this sector is not only prone to high levels of GHG emissions but also responsible for 70% of water abstraction (Fitton et al., 2019).

Deforestation is one of the main reasons for the increase in GHG caused by anthropic sources. This deforestation is linked to forestry and agriculture, which had an increase in their demands driven by foreign markets such as China, for example, which is Brazil's biggest commercial client. In the period between 2010 and 2014, 2.6 Gt $CO_2$/year were released, and beef and oilseed products were responsible for more than half of these emissions into the atmosphere (Pendrill et al., 2019).

### *GHG Emissions in the Energy Sector*

The increase in GHG emissions has a direct relationship with energy consumption and economic growth. The more economically developed a country gets, the more greenhouse gasses it emits. Organizations need to review their economic growth policies because this growth is linked to infrastructure, industrialization, urbanization, improvement in transport, among others. Besides, for this growth to occur, the use of energy sources that are often non-renewable, such as oil and coal, are the ones used in urban mobility (cars, trains, buses, metro) as they are used by industries (Waheed; Sarwar; Wei, 2019).

In 2016, Brazil wasted 47.4 TWh due to energy inefficiency. The commercial sector is the largest consumer of energy in the country and was responsible for 36% of the total waste generated. Due to the improvement in the economy, an increase in global demand for energy is expected in the order of 37% for the year of 2040 (De Oliveira Moraes; Machado; Silva, 2019).

### *GHG emissions in the Land-use Change Sector*

Brazil is one of the world's largest agricultural producers, yet part of this growth is a result of deforestation and fires in natural ecosystems. This development is due to factors such as subsidies to rural credit, the creation of the Brazilian Agricultural Research Corporation (Embrapa) which is responsible for research on improving agriculture, the National Plan for the Integration of the Amazon, and investments in machinery and logistical distribution. The

Brazilian agricultural sector is responsible for more than 20% of the Brazilian GDP (Stabile et al., 2019).

Excessive cattle ranching has led them to graze in the forests and they compete for water and food with the animals that are native to the region. Livestock has expanded in recent years throughout the Brazilian semi-arid zone, through rural properties. This animal breeding, which is often carried out by inefficient management, has caused environmental degradation, that damages the region's soil. To minimize these problems, farmers use natural habitats for grazing animals, causing problems in natural regions such as the Caatinga, for example (Dias; Massara; Bocchiglieri, 2019).

### *GHG emissions in the Industrial Processes Sector*

The use of various energy sources is important for industrial growth because it is part of company costs. In 2016, sugarcane had a share of 17.5% in the Brazilian energy matrix. This was the second highest result, considering that, in 2009, it reached the level of 18.1%. There are also many benefits of sugarcane mills, namely: the generation of jobs, movement in the economy, and clean energy from the burning of sugarcane bagasse. Ethanol is also used today mainly to fuel small and medium-sized vehicles. Thus, simulations were carried out and several scenarios were seen where a reduction in oil consumption, in the order of 3.8 to 13.7%, led to a reduction from 1.5 to 5.6% of GHG emissions, when compared to 2014, thanks to the use of ethanol (Zang; Martins; da Fonseca-Zang, 2018).

In the European Union (EU) the industrial sector represented 25% of all energy used. In Sweden, for instance, this value reached 38% in 2016. Studies have been done regarding energy efficiency in the wood industry, which has shown to be favourable for energy savings. In the case of Ireland, for example, studies have shown that the main source of GHG emissions was concentrated in the electricity used for industrial processing (Johnsson et al., 2019).

### *GHG Emissions in the Waste Sector*

Municipal solid waste (MSW) needs to be managed efficiently, as GHG is emitted in the decomposition process. This management is a global concern; countries like Africa have been promoting the efficient management of these compounds in the last two decades. The emission of a greater or lesser amount of GHG depends on the composition of the waste (amount of carbon present in it), as well as the form of disposal and the technology used for its treatment (Moura et al., 2015).

The amount of MSW in Brazil has increased in the last decade, from 0.5 kg/person to 1.7 kg/person. The production of energy used in these wastes is more attractive and has become part of the management of city halls (Rizwan et al., 2019).

## Materials and methods

The study objects can be divided into two categories: (1) GHG emissions in the Agriculture, Energy, Land-use Change, Industrial Processes, and Waste sectors; and (2) Brazilian annual energy balance. Through these two groups, it was possible to build the simulation using System Dynamics (SD). From the simulation onwards, the system was analysed.

### *Variables*

The variables that were analysed were also divided into two groups:

**Group 1)** GHG Emissions, comprised of: $CO_2$ – Energy Sector, $CO_2$ – Agriculture Sector, $CO_2$ – Land-use Changes Sector, $CO_2$ – Industrial Processes Sector, and $CO_2$ – Waste Sector;

**Group 2)** Brazilian Annual Energy Balance, comprised of: External Energy Sources, Renewable Energy Sources, Non-Renewable Energy Sources, Energy Consumption, Fuel Burning, and Fugitive Emissions.

### *Sample*

The data that were extracted from the tables to develop the simulation relate to the period from 1990 to 2020. These data were obtained from the websites: http://seeg.eco.br for GHG emissions, and http://epe.gov.br/pt for surveying the energy balance. Regarding data processing, they were treated *via* the statistical analysis software StatPlus:mac, from Analyst Soft, version 8 (https://www.analystsoft.com/br/). Excel, from Microsoft Office, was used to build tables and to perform Student's t-distribution analysis of the simulated values to determine if the simulation mean was equivalent to the mean of the values provided by the websites. To perform the simulation through System Dynamics, the Academic version of the AnyLogic Software was used.

### *Measurement Instrument and Technique*

Having done this data collection, as described in the previous subchapter, it is worth mentioning that the period under study is between 1990 and 2030 since, in COP 26, it was stipulated that countries should reduce their GHG emissions by 2030. Considering that the used databases did not show, at the time of this study, the values for 2021 – 2030, these numbers were obtained through simulation.

After collecting the data, StatPlus:mac version 8 was used in order to obtain the equation that best represented the data. An equation was obtained for each of the variables in Group 1) GHG emissions, and Group 2) Brazilian annual energy balance. After obtaining the equations, Excel was used to analyse the Student's t-distribution, which allows the assessment of whether the average of the values obtained on the simulation corresponds to the average of the real values. The two-tailed value was also calculated, which must be greater than 0.05 to correspond to 95% confidence in the data.

After the validation of the data by the Student's t-distribution, a model was built for simulation using System Dynamics. For the construction of the model, the academic version of the AnyLogic software was used. Two possible scenarios were built:

**Scenario 1** - The simulation was carried out with the equations obtained from the tables in order to verify the behaviour of the model, until the year of 2020;

**Scenario 2** - The model was simulated until the year of 2030, in order to verify the behaviour of GHG emissions.

### *Work Hypothesis*

Based on the information collected, it is possible to raise some important hypotheses for the work.

- GHG emissions in Brazil come from five sectors, among them the Land-use Change and Forests Sector should be the one that contributes the most to greenhouse gas emissions, due to the country having a problem with illegal deforestation;
- The Energy Sector should also be among the top three most emitting sectors, because the Brazilian energy matrix is composed of more than 50% of non-renewable energy sources.

## Results and discussion

The result of the work can be divided into four stages. In the first stage, the GHG emissions in Brazil were identified relating to the period from 1990 to 2020. In the second stage, the Energy Sources used in Brazil and the Energy Demand for that same period were raised. In the third stage, a model based on System Dynamics for GHG emissions in Brazil was build, while in the fourth stage, two possible scenarios were framed and analysed. The details of each step have been described throughout this chapter.

This first step consisted of identifying the GHG emissions ($CO_2$) for the five main sectors: Energy, Agriculture, Land-use Changes, Industrial Processes, and Waste.

For the Industrial Processes Sector, Table 1 compiles all emissions, ranging from hydrofluorocarbons (HFCs), chemical industry, mineral products, metal products, use of solvents, to non-energy fuels.

**Table 1.** $CO_2$ for Industrial Processes

| Year | Industrial Processes | Simulation |
|---|---|---|
| 1990 | 51,477,512 | 55,496,419 |
| 1991 | 57,896,199 | 57,204,040 |
| 1992 | 56,419,636 | 58,911,660 |
| 1993 | 60,673,021 | 60,619,281 |
| 1994 | 61,332,483 | 62,326,901 |
| 1995 | 64,593,823 | 64,034,522 |
| 1996 | 67,315,803 | 65,742,142 |
| 1997 | 68,656,271 | 67,449,763 |
| 1998 | 71,370,732 | 69,157,383 |
| 1999 | 71,500,264 | 70,865,004 |
| 2000 | 74,145,829 | 72,572,625 |
| 2001 | 71,730,075 | 74,280,245 |
| 2002 | 75,570,910 | 75,987,866 |
| 2003 | 76,605,905 | 77,695,486 |
| 2004 | 81,170,395 | 79,403,107 |
| 2005 | 80,506,035 | 81,110,727 |
| 2006 | 80,819,581 | 82,818,348 |
| 2007 | 84,267,196 | 84,525,969 |
| 2008 | 83,705,270 | 86,233,589 |
| 2009 | 76,137,835 | 87,941,210 |
| 2010 | 95,548,481 | 89,648,830 |
| 2011 | 99,817,934 | 91,356,451 |
| 2012 | 100,861,779 | 93,064,071 |
| 2013 | 100,989,465 | 94,771,692 |
| 2014 | 103,043,879 | 96,479,312 |
| 2015 | 102,089,517 | 98,186,933 |
| 2016 | 95,828,303 | 99,894,554 |
| 2017 | 99,912,515 | 101,602,174 |
| 2018 | 101,008,899 | 103,309,795 |
| 2019 | 99,472,614 | 105,017,415 |
| 2020 | 99,964,388 | 106,725,036 |

$CO_2$ emission values for Industrial Processes and for other processes together with their corresponding simulation are in the $CO_{2e}$ (t) GWP AR5 unit. To obtain the simulated values, a trend analysis was performed and, from it, Equation 1 was obtained.

$$IndustrialProcesses = -3{,}342{,}668{,}496.38307 + 1{,}707{,}620.56048 * Year \quad (1)$$

The values generated by Equation 1 can be seen in Table 1 in the 'Simulation' column. To validate the values obtained, the Student's t-distribution was used, that presented, for all cases, rejected values for those different than zero, which implies that the averages of the simulations correspond to the averages of the original values.

The next sector that was analysed was Land-use Change. Table 2 compiles all emissions ranging from land-use change and forestry, liming, removal in protected areas, removal by secondary forests, removal by land-use change, removal by secondary vegetation, removal of protected areas, and forest residues.

**Table 2.** Emission of $CO_2$ for Change in Land Use and Forest

| Year | Land and Forest Use Change | Simulation |
|---|---|---|
| 1990 | 1,391,025,917 | 1,703,016,834 |
| 1991 | 1,466,475,579 | 1,695,754,743 |
| 1992 | 1,715,718,595 | 1,686,362,698 |
| 1993 | 1,539,030,099 | 1,674,840,700 |
| 1994 | 1,697,561,928 | 1,661,188,747 |
| 1995 | 1,927,273,454 | 1,645,406,841 |
| 1996 | 1,650,903,500 | 1,627,494,981 |
| 1997 | 1,632,425,872 | 1,607,453,166 |
| 1998 | 1,591,234,952 | 1,585,281,398 |
| 1999 | 1,633,683,470 | 1,560,979,676 |
| 2000 | 1,535,605,023 | 1,534,548,000 |
| 2001 | 1,459,365,054 | 1,505,986,370 |
| 2002 | 1,753,054,747 | 1,475,294,786 |
| 2003 | 2,102,712,334 | 1,442,473,248 |
| 2004 | 2,048,174,166 | 1,407,521,757 |
| 2005 | 1,709,241,145 | 1,370,440,311 |
| 2006 | 1,305,148,371 | 1,331,228,911 |
| 2007 | 1,056,264,686 | 1,289,887,558 |
| 2008 | 1,013,338,908 | 1,246,416,250 |
| 2009 | 729,493,381 | 1,200,814,989 |
| 2010 | 678,977,243 | 1,153,083,774 |
| 2011 | 666,489,361 | 1,103,222,604 |
| 2012 | 703,722,040 | 1,051,231,481 |
| 2013 | 814,810,343 | 997,110,404 |
| 2014 | 789,917,764 | 940,859,373 |
| 2015 | 871,038,630 | 882,478,388 |
| 2016 | 932,444,875 | 821,967,449 |
| 2017 | 743,756,570 | 759,326,557 |
| 2018 | 762,740,767 | 694,555,710 |
| 2019 | 806,996,124 | 627,654,909 |
| 2020 | 997,923,296 | 558,624,155 |

To obtain the simulated values, a trend analysis was performed and, from it, Equation 2 was obtained.

$$LanduseChange{,}\wedge Forestry = -4.20338E + 12 + 4{,}232{,}411{,}201.00000 * Year - 1{,}064{,}976.96350 * Year^2 (2)$$

Values generated by Equation 2 can be seen in Table 2 in the 'Simulation' column.

The following analysed sector was Agriculture. Among the emissions from Agriculture, there are: rice cultivation, enteric fermentation, management of animal waste, burning of agricultural residues, and agricultural soils. These factors are seen in Table 3.

**Table 3.** $CO_2$ Emission for Agriculture

| Year | Agriculture | Simulation |
|---|---|---|
| 1990 | 1,391,025,917 | 1,703,016,834 |
| 1991 | 1,466,475,579 | 1,695,754,743 |
| 1992 | 1,715,718,595 | 1,686,362,698 |
| 1993 | 1,539,030,099 | 1,674,840,700 |
| 1994 | 1,697,561,928 | 1,661,188,747 |
| 1995 | 1,927,273,454 | 1,645,406,841 |
| 1996 | 1,650,903,500 | 1,627,494,981 |
| 1997 | 1,632,425,872 | 1,607,453,166 |
| 1998 | 1,591,234,952 | 1,585,281,398 |
| 1999 | 1,633,683,470 | 1,560,979,676 |
| 2000 | 1,535,605,023 | 1,534,548,000 |
| 2001 | 1,459,365,054 | 1,505,986,370 |
| 2002 | 1,753,054,747 | 1,475,294,786 |
| 2003 | 2,102,712,334 | 1,442,473,248 |
| 2004 | 2,048,174,166 | 1,407,521,757 |
| 2005 | 1,709,241,145 | 1,370,440,311 |
| 2006 | 1,305,148,371 | 1,331,228,911 |
| 2007 | 1,056,264,686 | 1,289,887,558 |
| 2008 | 1,013,338,908 | 1,246,416,250 |
| 2009 | 729,493,381 | 1,200,814,989 |
| 2010 | 678,977,243 | 1,153,083,774 |
| 2011 | 666,489,361 | 1,103,222,604 |
| 2012 | 703,722,040 | 1,051,231,481 |
| 2013 | 814,810,343 | 997,110,404 |
| 2014 | 789,917,764 | 940,859,373 |
| 2015 | 871,038,630 | 882,478,388 |
| 2016 | 932,444,875 | 821,967,449 |
| 2017 | 743,756,570 | 759,326,557 |
| 2018 | 762,740,767 | 694,555,710 |
| 2019 | 806,996,124 | 627,654,909 |
| 2020 | 997,923,296 | 558,624,155 |

To obtain the simulated values, a trend analysis was performed and, from this, Equation 3 was obtained.

$$Agriculture = -1.25919E + 10 + 6{,}523{,}945.96492 * Year (3)$$

As with all others, the values generated by Equation 3 can be observed in Table 3 in the 'Simulation' column.

The next sector that was analysed was Waste, which complies emissions from liquid effluent treatment and emissions from solid waste. The sum of all these factors can be seen in Table 4.

**Table 4.** Emission of $CO_2$ for Waste

| Year | Waste | Simulation |
|---|---|---|
| 1990 | 28,306,937 | 27,084,351 |
| 1991 | 29,761,259 | 29,300,721 |
| 1992 | 31,274,028 | 31,517,091 |
| 1993 | 32,864,472 | 33,733,460 |
| 1994 | 34,721,836 | 35,949,830 |
| 1995 | 36,878,251 | 38,166,200 |
| 1996 | 39,119,779 | 40,382,570 |
| 1997 | 41,182,542 | 42,598,939 |
| 1998 | 43,592,223 | 44,815,309 |
| 1999 | 46,256,739 | 47,031,679 |
| 2000 | 49,153,900 | 49,248,049 |
| 2001 | 54,015,026 | 51,464,418 |
| 2002 | 52,455,723 | 53,680,788 |
| 2003 | 57,013,567 | 55,897,158 |
| 2004 | 58,670,869 | 58,113,527 |
| 2005 | 61,883,529 | 60,329,897 |
| 2006 | 65,568,180 | 62,546,267 |
| 2007 | 66,391,658 | 64,762,637 |
| 2008 | 67,830,844 | 66,979,006 |
| 2009 | 70,486,430 | 69,195,376 |
| 2010 | 71,991,842 | 71,411,746 |
| 2011 | 73,429,482 | 73,628,115 |
| 2012 | 74,343,103 | 75,844,485 |
| 2013 | 77,652,222 | 78,060,855 |
| 2014 | 80,025,427 | 80,277,225 |
| 2015 | 83,006,748 | 82,493,594 |
| 2016 | 84,617,157 | 84,709,964 |
| 2017 | 86,418,776 | 86,926,334 |
| 2018 | 88,866,740 | 89,142,704 |
| 2019 | 90,399,713 | 91,359,073 |
| 2020 | 92,047,809 | 93,575,443 |

To obtain the simulated values, a trend analysis was performed and, from it, Equation 4 was obtained.

$$Waste = -4{,}383{,}491{,}397.45364 + 2{,}216{,}369.72298 * Year (4)$$

Once again, the values generated by Equation 4 can be observed in Table 4 in the 'Simulation' column.

Finally, the last analysed sector was Energy. Unlike the other sectors, this one in particular is directly related to the sum of two variables, which are "Fuel Burning" and "Fugitive Emissions". The sum of these two variables can be seen in Table 5.

**Table 5.** $CO_2$ for Energy

| Year | Energy | Simulation |
|---|---|---|
| 1990 | 193,673,138 | 211,460,478 |
| 1991 | 198,074,482 | 211,603,147 |
| 1992 | 202,161,932 | 213,519,404 |
| 1993 | 206,611,091 | 217,069,674 |
| 1994 | 215,012,707 | 222,114,379 |
| 1995 | 230,554,045 | 228,513,943 |
| 1996 | 248,323,052 | 236,128,787 |
| 1997 | 265,038,598 | 244,819,336 |
| 1998 | 272,734,576 | 254,446,012 |
| 1999 | 283,356,042 | 264,869,238 |
| 2000 | 289,813,577 | 275,949,438 |
| 2001 | 299,657,684 | 287,547,034 |
| 2002 | 297,658,475 | 299,522,450 |
| 2003 | 290,217,004 | 311,736,108 |
| 2004 | 306,194,013 | 324,048,432 |
| 2005 | 317,645,744 | 336,319,844 |
| 2006 | 321,130,079 | 348,410,767 |
| 2007 | 335,132,690 | 360,181,626 |
| 2008 | 354,212,901 | 371,492,841 |
| 2009 | 342,103,628 | 382,204,838 |
| 2010 | 371,944,836 | 392,178,038 |
| 2011 | 385,361,155 | 401,272,865 |
| 2012 | 418,850,273 | 409,349,742 |
| 2013 | 453,705,252 | 416,269,091 |
| 2014 | 478,782,917 | 421,891,337 |
| 2015 | 455,716,185 | 426,076,901 |
| 2016 | 422,288,563 | 428,686,207 |
| 2017 | 429,805,371 | 429,579,678 |
| 2018 | 408,631,213 | 428,617,737 |
| 2019 | 412,466,746 | 425,660,806 |
| 2020 | 393,705,259 | 420,569,310 |

Therefore, the first objective of this work, which was to identify GHG emissions in Brazil by sector starting from the year of 1990 up until 2020, was completed.

In order to meet the second objective of the project, the second stage was started, comprising of the execution of the Brazilian annual energy balance. For that, the Energy Sources used in Brazil and the country's Energy Demand for the period of 1990 to 2020 were raised.

The first sources to be worked on were the Non-Renewable Energy Sources that are concentrated in production, ranging from: oil, natural gas (or fossil gas), coal, steam coal, metallurgical coal, uranium ($U_3O_8$), to other non-renewable sources. Next, Renewable Energy Sources were considered: hydraulic energy, firewood, sugar cane products, wind, solar, and other renewable energy sources. The third step was to consider the External Energy Sources, that is, energy from other countries. In the decade of 1990, there was still a significant use of external sources that had been losing strength as the Brazilian energy matrix opened up to renewable sources.

Finally, the last item of the Energy Balance deals with the Internal Energy Demand, which is linked to the Energy Consumption variable. The reason for this link is that, as the country develops, the demand for energy increases. The values referring to Energy Consumption can be seen in Table 6.

**Table 6**. Energy Consumption

| Year | Energy Consumption | Simulation |
|---|---|---|
| 1990 | 141,211,93 | 132,085,46 |
| 1991 | 142,282,24 | 137,737,24 |
| 1992 | 142,661,05 | 143,389,01 |
| 1993 | 144,487,51 | 149,040,79 |
| 1994 | 152,321,13 | 154,692,57 |
| 1995 | 149,715,19 | 160,344,34 |
| 1996 | 156,019,67 | 165,996,12 |
| 1997 | 172,588,13 | 171,647,90 |
| 1998 | 176,022,73 | 177,299,68 |
| 1999 | 176,210,31 | 182,951,45 |
| 2000 | 179,642,79 | 188,603,23 |
| 2001 | 186,431,20 | 194,255,01 |
| 2002 | 192,872,30 | 199,906,78 |
| 2003 | 199,811,18 | 205,558,56 |
| 2004 | 215,498,25 | 211,210,34 |
| 2005 | 219,350,35 | 216,862,12 |
| 2006 | 227,177,83 | 222,513,89 |
| 2007 | 239,681,77 | 228,165,67 |
| 2008 | 248,754,26 | 233,817,45 |
| 2009 | 240,054,16 | 239,469,22 |
| 2010 | 257,492,03 | 245,121,00 |
| 2011 | 259,135,43 | 250,772,78 |
| 2012 | 268,645,53 | 256,424,56 |
| 2013 | 282,462,19 | 262,076,33 |
| 2014 | 287,193,90 | 267,728,11 |
| 2015 | 281,593,52 | 273,379,89 |
| 2016 | 273,729,28 | 279,031,67 |
| 2017 | 273,982,65 | 284,683,44 |
| 2018 | 275,994,19 | 290,335,22 |
| 2019 | 278,827,62 | 295,987,00 |
| 2020 | 280,875,33 | 301,638,77 |

To obtain the simulated values, a trend analysis was carried out and, from it, Equation 5 was obtained.

$$EnergyConsumption = -11{,}114{,}951.15045 + 5{,}651.77719 * Year \quad (5)$$

The values generated by Equation 5 can be observed the 'Simulation' column on Table 6.

The second objective of the work, which was to carry out the Brazilian annual energy balance from the year of 1990 to 2020, was thus completed.

The third stage of the results consisted in the elaboration of a model based on Systems Dynamics for GHG emissions in Brazil. After obtaining the equations referring to GHG emissions and the equations referring to the energy balance, it was possible to build, using the AnyLogic software, a model that represents the interaction of the two macro situations (Energy Production and Greenhouse Gas Emissions). The model can be seen in Figure 1.

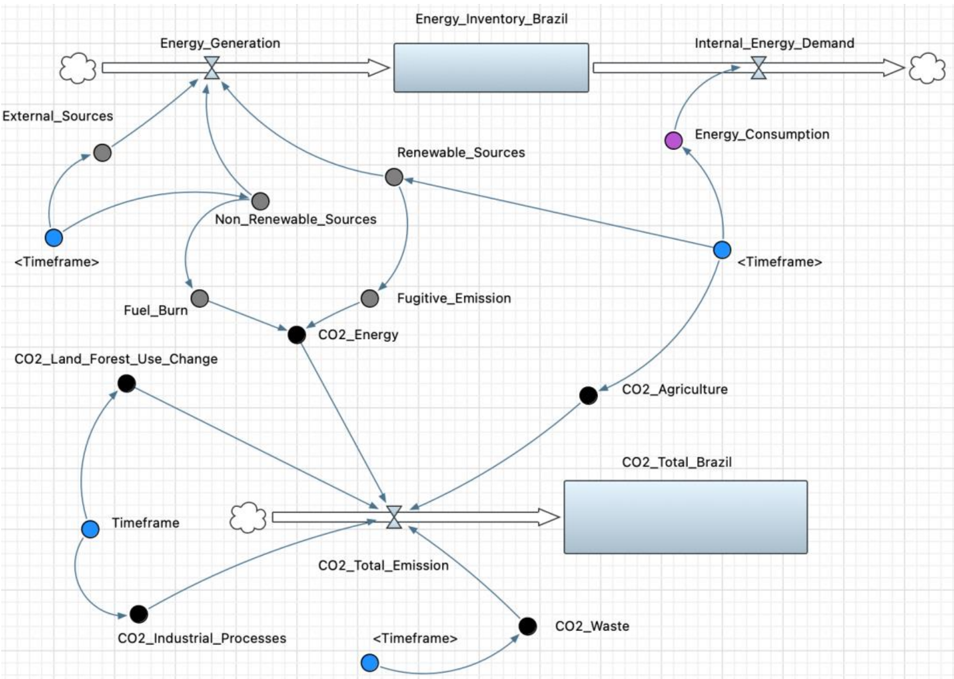


**Figure 1.** GHG emissions in Brazil in the period ranging from 1990 to 2020.

Using the System Dynamics technique and through the mathematical equations shown in this chapter, it was possible to build a model that correlates energy production in Brazil with GHG emissions. By international convention, GHGs are represented in terms of $CO_2$. 'Brazil Energy Stock' represents the energy balance and 'Total $CO_2$' represents the total GHG released by Brazil, for the period determined in this study. This model presented in Figure 1 meets the third objective of the work, which was build a model for simulation of GHG emissions in Brazil.

The last stage of the results consisted of building and analysing two possible scenarios. For Scenario 1, the simulation was performed with the equations obtained from the tables in order to verify the behaviour of the model. For Scenario 2, the model was simulated until the year of 2030, in order to verify the behaviour of GHG emissions.

In Scenario 1 (Simulation of the GHG model 1990 – 2020), it was observed:

- The energy stock in Brazil increases over the years and, from 1995 onwards, it is possible to observe an accumulation of energy, as displayed on Figure 2.
- CO2 emission has been reducing over time on a significant scale, as can be seen in Figure 3.

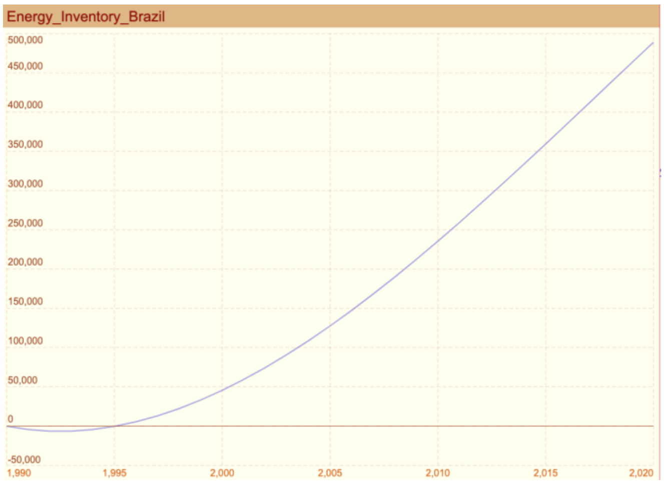


**Figure 2.** Energy Stock in Brazil ranging from the year of 1990 to 2020

The fact that the energy stock increased is due to energy production. In this case, the renewable energy source has a representativeness of 41.2% against 58.7% of the non-renewable energy sources. Energy consumption has also been increasing over time, but at a slower pace, which provides a reserve over the years.

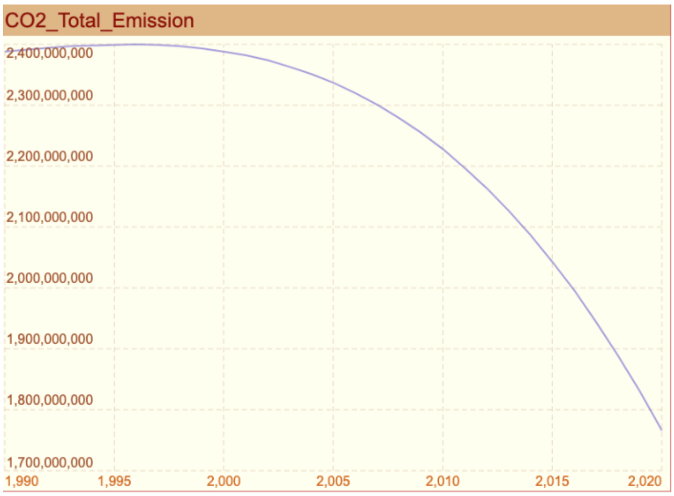


**Figure 3.** Total $CO_2$ emissions in Brazil ranging from the year of 1990 to 2020

The reduction in the Total CO2 is due to the reduction in the emissions from Forestry and other land use, which has been reducing over the years and has a significant share in the Total CO2, as can be seen in Figure 4.

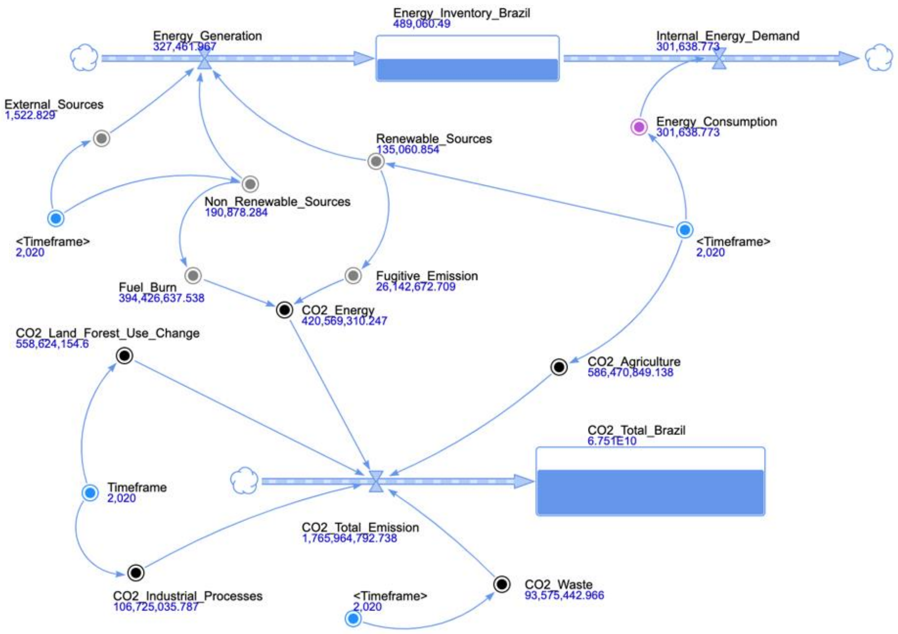


**Figure 4.** Scenario 1: Total $CO_2$ in Brazil from the years of 1990 to 2020

From Figure 4, one can perceive the direct and indirect relationships of the GHG emission sources for the period of 2020. Therefore, the first scenario is representative.

The second scenario deals with emissions up until the year of 2030. Because data from 2021 to 2030 are not available at the time of this study, these were simulated using the same data used to generate the first scenario. The simulation time of the model, however, was changed in AnyLogic, starting in 1990 and ending in 2030, as displayed in Figure 5.

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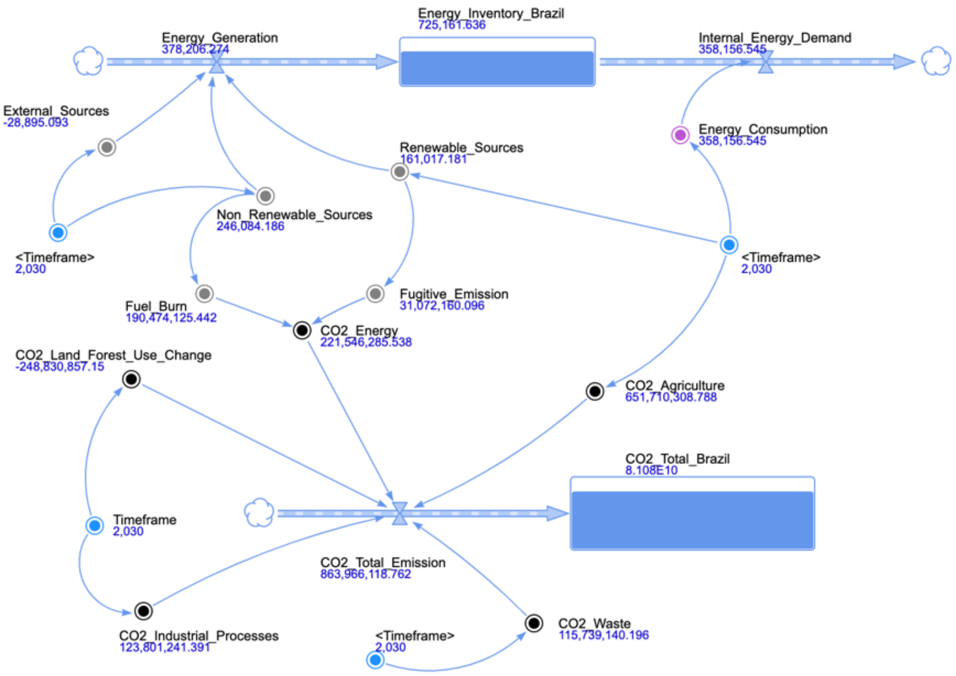


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**Figure 5.** Scenario 2: Total $CO_2$ in Brazil from the years of 1990 to 2030

As shown by Figure 5, there is a significant reduction in GHG emissions in Brazil, related to Forestry and other land use. If this variable reaches zero as of the year of 2027, the GHG emission reduction will be in the order of 48.92%, a significant value in terms of greenhouse gas emissions.

The energy sector also contributes to the total reduction of GHG. As it can be seen on Figure 6, the plateau of the graph occurs precisely in 2017 and, from that moment on, gas emissions begin to decline year by year.

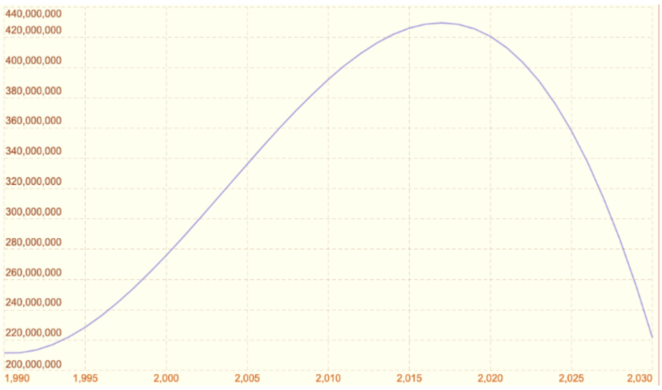


**Figure 6.** Energy $CO_2$ emissions in Brazil ranging from the year of 1990 to 2030

This reduction is partly due to the adoption of an energy matrix that uses renewable sources and, therefore, it is less polluting.

Another important point to note is that emissions in the Agriculture sector, which also has a significant share since Brazil is one of the largest exporters in this sector, must be taken into account otherwise the country will not be able to reduce emissions any further.

With the proposal of the two possible scenarios presented in this chapter, the last objective of the work (to propose and analyse two possible scenarios for GHG emissions in Brazil) is concluded.

After developing the four proposed objectives, it is possible to analyse the results obtained with studies that were already published.

The first stage of this study was obtaining and validating the equations for building the model to be simulated. The equations were important because they allowed a mathematical representation of reality and, with their use, it was possible to propose two scenarios. In these scenarios, once can perceive the energy demand in Brazil. The simulation developed in this work complements the study by the authors Mercure et al. (2019), where it is evidenced that the population growth together with the increase in income is increasing the demand for energy in the country.

The second result concerns the simulated scenarios. In Scenario 1, it was possible to see an overview of how energy production behaved in Brazil and how GHG emissions worked in that period. It was possible to observe that, over the years, Brazil adopted a policy of using non-renewable resources such as oil, because it needed relatively cheap energy to meet the domestic demand that grew every year, reaching its peak emission in 2004. After that period, emissions began to decrease, largely due to stipulations by the Climate Summit and the UN.

These results are in line with publications that have already warned about this problem, such as the study by the authors De Oliveira Moraes, Axe and Silva (2019), who demonstrated that there is a waste of energy in Brazil caused by energy inefficiency, and that the commercial sector in 2016 was responsible for 36% of the total waste. Another study that complements Scenario 1 was that of the authors Waheed, Sarwar and Wei (2019), where their research demonstrates that the use of non-renewable energy is linked to the use of urban mobility (cars, trains, buses, subways) and the industries. The authors emphasize the need for organizations to review their economic growth policies, as this growth is linked to infrastructure, industrialization, urbanization, and improved transport.

In Scenario 2, it is possible to see the reduction in GHG emissions for the years after 2020, which is linked to two sectors, Energy and Land Use and Forestry, which together, if treated more efficiently, can reduce emissions by approximately 48.9 %. The study carried out by Empresa de Pesquisa Energética (EPE, 2019) identified that the Brazilian energy matrix is diversified and that, in 2018, renewable energies had a share of 45.3%, while non-renewable energies had that of 54.7%, highlighting oil and its derivatives, which represented 34.4%.

Another study that corroborates Scenario 2 is that of the authors Neri et al. (2019), who showed that Brazil is the 8th producer of wind energy in the world, producing 13.3 GW of this type of energy (the main wind energy producer is the Northeast region of Brazil). Brazilian wind energy in 2017 avoided the emission of 17.8 million tons of GHG into the atmosphere, a value that represents the equivalent emission of 12 million cars.

## Conclusions

With the increase in terrestrial temperature caused by GHG emissions, it is clear that actions to mitigate the problem need to be taken. Organizations such as the Climate Summit and the UN itself are important to set goals for countries to reduce emissions on the planet.

Studies like this work are important to show the actions that can be taken as well as evaluate possible scenarios. In this specific case, the greenhouse gasses released by Brazil between the years of 1990 up until 2030 were the subject of this work. Four specific objectives were proposed: (1) Identify GHG emissions in Brazil by sector from the year of 1990 to 2020; (2) Carry out the Brazilian annual energy balance from 1990 to 2020; (3) Build a simulation model for GHG emissions in Brazil, and (4) Propose and analyse two possible scenarios for GHG emissions in Brazil. All objectives were accomplished and brought a new perspective through System Dynamics that was to analyse energy production in Brazil together with GHG emissions.

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