**Greening the Brazilian energy grid as a sustainable response to increasing consumption: how feasible and how costly?**

**Draft – don't quote please**

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**Abstract:** This paper estimates the $CO_2$ emission and economic gains of different ways of altering the Brazilian energy production and consumption system. Based on sectorial data and the Brazilian Decennial Energy Plan, we use a recursive computable general equilibrium model to simulate the trajectory of the main macroeconomic compounds (Gross National Product, household consumption, investment, exports, imports, employment, and inflation), gains in welfare indicators, and $CO_2$ emissions by 2026. These trajectories are computed under two different scenarios: increased energy and consumption efficiency, and inflated wind-solar grid. Despite the slower economic growth when compared to the first scenario, the latter would render larger gains for household consumption among the poorer families. Policy implications are discussed on the importance of these changes to the success of multilateral international agreements and the future of Brazilian leadership on climate-related adaptation policies.

**Keywords:** low carbon economy; energy efficiency; water-wind-solar energy grid; climate change; computable general equilibrium model

## 1. Introduction

As climate change advances, governments, industries, and the civil society seek strategies to adapt to or mitigate the current and expected adverse effects, exploring institutional and technological mechanisms to curb carbon emissions without compromising economic development. This is a very difficult equation to solve, since many barriers to mitigation and adaptation have to be simultaneously broken, from normative and political, to technical and economic barriers (Biesbroek et al. 2013). Because economies are increasingly dependent on energy, and many of these energy sources are carboniferous, the adoption of either energy efficient technology or a low-carbon energy system is key to achieve environmental sustainability without sacrificing economic development. The way alternative schemes for energy production and consumption are done, however, may either increase or decrease carbon emissions, despite the associated gains in economic performance (Jacobson et al. 2015, Sorrell 2009; Brookes 2000).

This paper estimates the $CO_2$ emissions and the economic impacts of different alternatives of altering the Brazilian energy production and consumption system by 2026. Based on sectorial data (input-output matrix) and the Brazilian Decennial Energy Plan guidelines, we use a recursive Computable General Equilibrium (CGE) model to simulate the real gains in the Brazilian Gross National Product (GNP), household consumption, and $CO_2$ emissions under two different policy scenarios: (1) increased efficiency in energy production and consumption (*efficiency gain*) and (2) inflated wind-solar grid (*compositional change*). The first scenario represents an effort to estimate how much a reduction in the energy efficiency gap in the Brazilian energy system would contribute to the country's economic performance and mitigation of carbon emissions in the coming decades. The second is in line with the expected increase in the share of clean energy sources (wind and sunlight) as described in the 2026 Brazilian Decennial Energy Plan, and reflects the great potential for increase in wind and sunlight energy generation (Simas and Paccas 2013). These two scenarios enable us to capture possible rebound effects from an increase in energy efficiency – where total productivity could lead to an increase in total consumption and associated greenhouse gas (GHG) emissions. Because our CGE model estimates the impact of the different scenarios on household consumption by income decile, it is also possible to analyze which (or if any) scenario leads to a more equitable trajectory of growth while transitioning to a low-carbon economy.

Brazil was chosen for four main reasons. First, the country experienced a booming economic period in the last 15 years, raising around 30 million individuals out of poverty. This sharp decline in poverty accounted for half of the economic mobility observed in Latin America in this period, increasing the middle class and its consumption needs (Word Bank 2016). As a result, Brazil became the largest greenhouse gas emitter among the Latin American countries (ECLAC 2009). Second, the country hosts the most biodiverse terrestrial ecosystem in the world, the Amazon, which is particularly sensitive to climate change. It is also a key component of the South American hydrological and climate system, providing humidity to the most productive agricultural areas of Brazil and contributing to temperature regulation on the entire continent (Malhi et al. 2009). Third, the energy sector in Brazil has considerable room for gains in energy efficiency (CNI 2009) and has developed an ambitious normative basis, through a wide range of programs, to foster energy efficiency and to increase the use of non-carboniferous energy sources (Tolmasquim 2012). Finally, most studies on the economic consequences of a greener energy grid are concentrated in developed countries. Understanding the benefits and costs associated with change in the future energy generating system among developing countries is a way to shed light on the environmental consequences of increased consumption as more individuals leave poverty in these countries and join the consumer market. Imposing restrictions on consumers' behavior in countries with the fastest rate of increase in the consumption base is not only more difficult, but may be less effective and morally questionable (Hertwich 2005; Lorek and

Spangenberg 2013). Change in the energy system may be a simpler and more effective way to help nations, regardless of their development stage, to meet their sustainable goals with minimum costs for the society (Jacobson et al. 2015).

In addition to this introduction, this paper is structured as follows. Section 2 discusses the implication of gains in energy efficiency for economic growth and carbon emissions, including the well-known Khazzoom-Brookes rebound effect. It also reviews simulation studies applying a compositional shift in the energy grid from predominantly fossil fuel based to carbon-low sources. Section 3 provides a detailed description of our CGE model specification and how each simulation scenario was defined. Section 4 presents and discusses the results of how the Brazilian economy would perform by 2026 under both scenarios in terms of the main macroeconomic compounds (real GNP, household consumption by income decile, investment, exports, imports, employment, and inflation), in addition to the annual trajectories of GHG emissions. Section 5 concludes the paper, discussing the implication of our results for equitable growth under a low-carbon economy and the role Brazil could play as one of the leaders for climate change mitigation and adaptation policies.

## 2. Energy Efficiency and Low Carbon Energy Grid

The two oil crises in the 1970s prompted a new level of concern about efficiency in the production and use of energy. It became clear that fossil fuel reserves could either face mid-term decrease in their production capacity or be subject to political instability among the leading producing countries, with direct consequences for commodity prices (Hancock and Vivoda 2014). This supply side shortage produced a new paradigm for energy efficiency – defined as the ability to use less energy inputs to achieve the same level of energy service (output). Industrial processes, cars, household appliances, and cooling/heating systems gradually adapted to this new paradigm, with important changes in the products' design, production technology, and consumers' behavior (Allcott and Mullainathan 2010; Patterson 1996).

Energy efficiency suddenly became a political agenda of governments due to its role in reducing the energy dependency of countries, increasing the stability of energy supply, and fostering more sustainable use of fossil and non-fossil fuel resources (Stern 2007). These changes would have not happened if they were not believed to be economically viable. Many studies in the 1980s and 1990s showed that changing the use of energy could increase profit if followed by technological gains (Thompson et al. 1981; Hirst and Brown 1990). As a result, new forms of energy emerged, such as wind and solar energy along with more advanced forms of energy supply, such as hydrogen battery cells (Biesbroek et al. 2013; Jacobson et al. 2016). By the end of the 1990's and throughout the 2000's, new research probed the environmental benefits of energy efficiency, suggesting that increase in efficiency would lead to more, and not less GHG emissions (Brookes 2000).

Based on the Jevons principle[1], the "Khazzoom-Brookes postulate" coined by Saunders (1992) suggests that, under not very demanding or restrictive assumptions, higher energy efficiency would increase energy demand at the aggregate level due to gains in overall factors productivity. Consequently, efficiency gains could accommodate higher prices at a higher level of consumption, increasing GHG emissions. If empirical evidence on the Khazzoom-Brookes effect is available for a specific setting, gains in efficiency seem the inappropriate way to curb carbon emissions (Khazzoom 1980; Brookes 1990; Greening et al. 2000), unless combined with efficient taxation, outlawing, or rationing of carboniferous energy sources[2] (Sorrell 2009).

[1] Quoting Brookes (2000: 357): "Jevons said, in writing about the danger of Britain running out of fuel, 'Nor will the economical use of coal reduce its consumption. On the contrary economy renders the employment of coal more profitable and thus the present demand for coal is increased… It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth.'"

[2]These measures, however, are difficult to pursue from a political perspective and are highly dependent upon the existence of substitutes to achieve economic efficiency (Brookes 2000).

The Khazzoom-Brookes (KB) rebound effect[3] will be stronger if the implicit reduction in production costs (or in the relative prices) happens in sectors where the price elasticity of energy demand is high. The KB effect will also be a consequence of the income effect: with lower energy prices, consumers and industries would have a larger disposable income and could increase consumption of other products that are energy demanding and less efficient[4]. Finally, change in the relative price for energy inputs may change their use, favoring sectors that are energy intensive, leading to a macroeconomic effect of increased demand for energy (Linares and Labandeira 2010). Gillingham et al. (2013) believe that the KB effect is overestimated in the literature, and argue that gains in efficiency can render a net benefit in terms of energy conservation.

With increased evidence of anthropogenic climate change, energy efficiency and conservation – especially among offending energy sources with low levels of substitutability – are now even more important for achieving sustainable development and meeting the ambitious global and national plans to curb GHG emissions (UNCTAD 2009). Although an increase in non-fossil energy sources is always a possibility (*compositional change*), the current technology for energy conservation and delivery represents a technical and economical barrier to adaptation, especially in economies where expected intertemporal rates of return are high for these technologies (Biesbroek et al. 2013). Thus, energy conservation and efficiency are still the main avenue for the energy sector to reduce GHG emissions.

Energy efficiency can be either the result of an overall technological progress underway – as a response to increasing energy or carbon price, or a government-induced process. Governments may put in practice a wide range of technological policies, such as subsidizing and

[3] In addition to the KB effect, the "energy efficiency gap" is the second paradox reported in the literature of energy efficiency. It relates to the slow pace or lack of implementation of efficiency measures, despite their apparent socioeconomic and environmental benefits. The reasons for why investment in efficiency and conservation is low are not clear, which leads to an unclear scenario of which policies are more adequate to promote them (Linares and Labandera 2010).

[4] Or react by simply increasing use of products and services.

funding of R&D, giving financial incentives to accelerate the rate of energy efficiency measures by industries, or providing guidelines for sectorial and residential consumption of energy efficient processes or products (Azar 2010). If appropriately implemented, these government interventions may promote cost-effective market-based low carbon production systems. The efficient use of energy also has the benefit of reducing the cost of products and services, increasing productivity and competitiveness in many economic sectors. Finally, it may promote social gains, such as an increase in employment and reduction in energy costs for low-income families, as well as political benefits, such as an increase in national security (Geller 2005).

Increase in the use of clean energy sources, such as nuclear power, wind, water, and sunlight, is another way to reduce GHG emissions, although its consequences for economic growth and safety may vary (Yang 2014). Many studies in the United States simulated the potential and consequences of an all-purpose energy infrastructure powered by Wind-Water-Sunlight (WWS) sources. Jacobson et at. (2016), for instance, estimate that if the American state of Washington adopted a 100% WWS powered all-purposes energy infrastructure, energy demand would decline approximately 40% by 2050. The decline in energy consumption would be followed by stabilization of energy prices. Families would also be benefited by saving about $85 per year in direct energy costs, and around $830 per year in health costs because of the reduction in air pollution and associated mortalities. These gains would be achieved with a very small increase in land (0.2%) to accommodate the expanded WWS infrastructure. Mason et al. (2010) found similar results by simulating the use of hydro, wind, geothermal, and biomass resources to make the electricity generation system of New Zealand 100% renewable. As in Mason et al. (2010), Hart and Jacobson (2011)'s simulation model applied to California suggests that a portfolio of renewable sources, coupled with emerging technologies, is able to provide large amounts of energy without an increase in energy generation. This can be achieved by an associated change in energy demand, vehicle-to-grid systems, and large-scale energy storage capable of responding to peaks.

Based on CGE models, studies highlight the limited macroeconomic gains from a compositional change in the renewable electric grid, especially among developed countries[5]. Boringer (2010) found limited prospects for employment and welfare gains in Germany. Despite having found an overall positive relation between the promotion of renewable energies, economic growth, and employment for Portugal, Fortes et. al (2015) highlight that this relation is not straightforward and may render negative impacts depending on the policy instruments and the financial mechanisms used. Results for developing countries are more promising, however. Ruamsuke et al. (2015) found that clean electricity generation technologies could provide positive impacts to Southeast Asian countries. Dai et al. (2105) also found significant green growth effects from renewable energy investments for the Chinese economy, with particularly large benefits for upstream industries.

One of the main concerns related to WWS sources is how to incorporate them into a power grid with minimum load loss, since they show large variation throughout the year and across space (Jacobson et al. 2015; Sovacool 2009). Based on a simulation model, Jacobson et al. (2015) argue that integration of WWS generated energy into the existing American grid would be able to deliver a low-cost and no-load-loss solution to the future of the country's energy generation. Accounting for future climate change scenarios of extreme events – which are important when considering the uncertainty associated with WWS sources, the WWS system could account for 96% of the future energy demand in the US, with no need for use of natural gas, biofuels, nuclear power, or stationary batteries. This is a promising result for other economies where WWS sources are widely available and alternative energy sources (such as

[5] There are exceptions, however. Rivers (2013) shows that reducing electricity sector emissions through renewable electricity policies is likely to increase the equilibrium unemployment rate in US.

batteries and nuclear power) may be difficult to implement. This is particularly the case for Brazil (Carvalho 2012; Simas and Paccas 2013).

In the Brazilian context however, moving towards a low carbon economy is more likely to be pursued by efficiency gains than by a shift in the energy grid composition. There are many reasons to believe that this would be the case. First, the economy has been in recession for many consecutive years, so moving to other forms of low-carbon energy seems less plausible due their higher costs of implementation. Second, hydroelectric plants dominate the national electric system (Carvalho 2012). These plants are cheaper to expand due to land availability, and generate smaller environmental impacts than fossil fuels (EPE 2007). Finally, Brazil still has room for large gains in efficiency in both hydroelectric and fossil fuel energy sources (Tolmasquim 2012). The idea that energy efficiency is quicker, cheaper, and a more sustainable energy supply to achieve sustainable development has been supported by many economists and energy engineers (UNCTAD 2009). The Intergovernmental Panel on Climate Change, for instance, estimates that 7 to 14% of global GHG emissions could be mitigated with negative costs if conservation and efficiency measures were adopted (IPCC 2007), although these figures do not come without criticism (Sorrell 2009).

The Brazilian government, through the Brazilian Plan on Climate Change and Brazil's Nationally Determined Contribution (NDC), established an aggressive goal of reducing emissions 37% below the 2005 levels by 2025[6]. This goal contrasts with reductions below business-as-usual (or an intensity target), like the ones agreed on by other large developing countries. In the NDC, Brazil sets out a clear plan to achieve its target, including the goal of reaching a 45% share of renewables in its primary energy mix by 2030 (Brazil Government 2015). The country has proposed to source 23% of power generation from renewable resources

[6] This goal corresponds to emissions of 1.3 $GtCO_2e$ by 2025, equivalent to 37% below 2005 emissions levels (Brazil Governement, 2015).

(not including hydropower) by 2030, comparing to 10% from these sources of energy by 2014. NDC further intends to promote new standards for clean technology and to enhance energy efficiency measures beyond the current technology used.

Despite the progress achieved in recent years and the establishment of a normative basis for the increase in energy efficiency (Tolmasquim 2012), Brazil still has room for large improvements in energy conservation, especially in the industrial, transportation, and residential sectors[7]. The industrial sector, for instance, has room for an increase in electric energy efficiency of 39% by 2030 (PNEf 2011). This sector has also a potential 4.5 larger for increase in energy conservation of non-electric sources, compared to electric energy sources (CNI 2009). The Brazilian gap in energy efficiency seems to have been only partially closed by the Brazilian Energy Plan and associated programs. To eliminate this gap, low carbon technologies have to yield higher return rates for the private sector, so this sector can lead investment in the area. Otherwise, call for principles of sustainability and social responsibility are likely to be insufficient for the private sector to increase the use of renewable energy such as WWS.

## 3. Methodology

### 3.1. BeGreen Model

The general equilibrium approach has been increasingly used to evaluate environmental and energy policies aimed to curb pollution and GHG emissions. These policies trigger changes in the agents' decisions on production and consumption as a response to altered prices, quantities, and the structure of the economy. The use of a computable general equilibrium (CGE) model makes it possible to analyze policies' impacts on macroeconomic variables, but also on income distribution and welfare (Wing 2004).

[7] The industrial sector is the largest energy consumer, responding for 35.8% of final consumption in 2012, followed by the transportation (30.0%) and residential (9.8%) sectors (Ben 2012).

The CGE model used in this study, called the BeGreen model, has three important features that make it ideal to evaluate energy policies. First, it incorporates a detailed specification of the energy sector. Second, it specifies an environmental module that can account for GHG emissions. Finally, it uses a recursive dynamic setup that allows for long run simulations. These features of CGE models are relatively new in the Brazilian literature. The model includes 124 products and 58 sectors, in addition to 14 final demand components. These components are household consumption for each of the 10 representative families[8], government consumption, investments, exports, and stocks for the three primary factors (capital, labor, and land), two margin goods (trade and transportation), imports by product for each one of the 58 sectors and 14 components of the final demand, and an aggregation of indirect taxes on production.

One of the distinguishing features of our CGE model is the hypothesis for modelling specific energy-intensive sectors and energy demand from other sectors. In our model, each sector can produce more than one product, which implies that it uses many types of energy inputs, intermediate inputs, and primary factors. Each sector has an optimizing behavior, choosing inputs that minimize the cost of production for a given level of product, subject to a technology that renders constant returns to scale.

We implemented a major enhancement of the theoretical production structure regarding the energy specification as an effort to move towards a more realistic, "bottom-up" approach in the modeling of energy-intensive sectors, known as the "Technological Bundle" (McDougall 1993; Hinchy and Hanslow 1996; Abare 1996). This is an innovation for the Brazilian CGE models, as it includes energy-intensive sectors where the input substituting options are relevant for production. Different technologies can be partially replaced, assuming imperfect

[8] The families are aggregated according to income deciles obtained from the Brazilian Household Budget survey data, totaling 10 representative families.

substitutability. Replacement is achieved through CRESH (constant ratio of elasticities of substitution, homotheticity) production functions (Hanoch 1971; Dixon et al. 1982).

The specification of a "technology bundle" poses a restriction on the substitution of inputs, making it consistent with the characteristics of well-known technologies. This restriction avoids the possibility of obtaining replacement or technically unfeasible combinations of inputs. Two sectors fall into this category due to their well-characterized production technologies: *Electricity generation* and *Steel and iron industry*. For all the other sectors, the technology representation allows for a large variety of substitutions among different types of fossil fuel and non-fossil energy sources, in addition to other intermediary inputs and primary factors. Sectors choose the composition of energy inputs from three composites: *renewable composite*, *self-generation of electricity*, and *non-renewable composite*[9]. Households are disaggregated according to income deciles (10 groups) as suggested by data from the Brazilian Consumer Expenditure Survey. This nationwide survey provides detailed information on household income and expenditures including electricity, gasoline, and other energy goods. In BeGreen, the household demand is specified by a non-homothetic Stone-Geary utility function (Peter et al., 1996). Demand equations are derived from a utility maximization problem whose solution follows hierarchical steps. In the first level, there is a constant elasticity of substitution (CES) between domestic and imported goods. At this level, the possibility of substitution between gasoline and alcohol was introduced through a CES function. This specification was chosen because of the real possibility of substitution, boosted by the increasing use of vehicles with flex-fuel technology in Brazil, whose composition depends on the relative prices of both products.

In the subsequent top level, there is a Klein-Rubin aggregation of the composed goods; so, the utility derived from consumption is maximized according to this utility function. This

[9] In the renewable composite, firms choose through a CES function renewable energy inputs (firewood, charcoal, alcohol, sugar cane bagasse, and hydropower). For the non-renewable composite, they choose among non-renewable inputs (oil, natural gas, LPG, diesel oil, fuel oil, gasoline, kerosene, coke, and other refinery products).

specification gives rise to the linear expenditure system (LES), in which the participation of expenses above the subsistence level for each good represents a constant proportion of the total subsistence expense for each household. The composition of consumption by domestic and imported products is controlled by CES functions.

The standard small country assumption is assumed, implying that Brazil is a price-taker in import markets. However, because the imported goods are differentiated from the domestically produced goods, the two varieties are aggregated using a CES function, based on the Armington assumption. Exports are linked to the demand curves negatively associated with domestic production costs and positively affected by an exogenous expansion of international income. Government consumption is typically exogenous and can be associated or not with household consumption or tax collection. Stocks accumulate, following the changes in production.

The specification of the recursive dynamic is based on the modeling of intertemporal behavior and results from previous periods (backward looking). Thus, investment and capital stock follows accumulation mechanisms and inter-sectoral shifts from pre-established rules associated with the depreciation rate and rates of return. Moreover, it assumes a dampening of the investment responses. The labor market also presents an intertemporal adjustment process involving three variables: real wages, current employment, and employment trends. On the supply side, a constant elasticity of transformation (CET) function is used to define the output of a given sector as a revenue-maximizing aggregate of goods for the domestic market and goods for the foreign markets.

BeGreen has an environmental module inspired by the MMRF-Green model (Adams et al., 2002). Emissions are associated with the use of the 12 different fuels available or sector activity, such as agricultural emissions[10] or industrial processes (e.g. cement manufacture). From

[10] Whose cause lies in the enteric fermentation of ruminants, rice cultivation, and use of fertilizers, an important source of Brazilian emissions.

the results of certain variables (fuel use by sectors, level of activity, and household consumption), the environmental module calculates changes in emissions. Emissions are measured in terms of carbon dioxide equivalents ($CO_2$-e). Emissions from fuel use are modeled proportionally to use and activity emissions for the product-related industries. The detailed module specification is provided as supplemental material.

### 3.1.1. Equilibrium conditions and closure rules

The market equilibrium conditions of BeGreen is characterized by an allocation of goods and factors in such a way that the endogenously determined prices clear all markets, and all agents respect their budget constraint. The supply–demand balances for all commodities and non-fixed factors clear through price adjustments in frictionless markets. The model is Walrasian in character, and hence it only determines relative prices. The nominal exchange rate is chosen to be the numéraire. The major macroeconomic variables are endogenous in the policy scenario, except for exogenously defined real government expenditure. In CGE recursive dynamic models, increases in investment cause reductions in the expected rates of return via an increase in capital stock, later reducing these investments to its steady state (equilibrium). On the other hand, real wages will respond to increases in employment until the balance of the labor market is reestablished. BeGreen is a one-country model with exogenous international trade structures. Therefore, Brazil is modelled as a small open economy.

### 3.1.2. Model Database and Parameters

The core database was built based on the 2005 Input-Output Matrix provided by the Brazilian Institute of Geography and Statistics (IBGE), foreign trade by sector and trade port provided by the Foreign Trade Secretariat (SECEX), and household consumption by product based on the 2002-2003 Brazilian Household Budget Survey[11] (IBGE, 2004). Emissions of $CO_2$-e are another important information in the database.

Table 1 (INCLUIR PARTICIPACAO DOS BENS ENERGETICOS POR GRANDES SETORES).

Table 2 (% DOS BENS ENERGETICOS NO CONSUMO DAS FAMILIAS)

Table 3 summarizes the BeGreen emissions data, which are based on information from the Brazilian Energy Balance and Emissions Inventory, indicating a volume of 882,018 Gg $CO_2$-e[12] in 2005 divided into 330,344 (37.5%) Gg $CO_2$-e from fuel use and 551,674 (62.5%) Gg $CO_2$-e from productive activities. *Livestock and Fishery* and *Agriculture and Others* represented together 75% of emissions among the productive activities in the country by 2005.

**Table 3 – Emissions associated to fuel usage and sectors in Brazil (base year 2005)**

| **Fuel Use** | **Emissions (Gg CO2-e)** | **Share (%)** | **Sectors (Productive Processes)** | **Emissions (Gg $CO_2$-e)** | **Share (%)** |
|---|---|---|---|---|---|
| Diesel | 98,470 | 30 | Livestock and Fishery | 332,515 | 60.3 |
| Gasoline | 39,073 | 12 | Agriculture and Others | 83,256 | 15.1 |
| Mineral Coal | 32,397 | 10 | Water and Urban Sanitation | 41,053 | 7.4 |
| Natural Gas | 30,014 | 9 | Steel Manufacturing and Derivatives | 38,283 | 6.9 |
| Charcoal | 25,618 | 8 | Oil and Gas | 15,967 | 2.9 |
| Fuel Oil | 21,026 | 6 | Cement | 14,349 | 2.6 |
| Alcohol | 16,973 | 5 | Chemical Products | 11,450 | 2.1 |
| Other of Oil Refining | 16,570 | 5 | Other Non-Metallic Products | 5,604 | 1.0 |
| Coke | 15,979 | 5 | Machinery and Equipment | 3,695 | 0.7 |
| Kerosene | 15,250 | 5 | Non-Ferrous Metals | 3,370 | 0.6 |
| Metallurgical Coal | 12,356 | 4 | Others of Mining | 1,896 | 0.4 |
| LPG | 6,618 | 2 | Electrical Machinery and Others | 146 | 0.0 |
| **Fuel Use Emissions** | **330,344** | **100 %** | **Productive Activity Emissions** | **551,674** | **100 %** |

Source: Author's elaboration based on the Brazilian National Inventory of Emission and Energy Balance Publications (MCT, 2010; MME, 2005).

[11] Although IBGE has a newer version of the Brazilian Household Budget Survey, fielded in 2008-2009, our consumption structure based on the 2002-2003 survey is more adequate to match the 2005 input-output matrix. Furthermore, the consumption structure did not change significantly in these 6 years (Domingues et al. 2015).

[12] Emission factors were needed to process the emissions in a common unit, $CO_2$ equivalent ($CO_2$-e), obtained from the Stern Review (Stern, 2006), which are derived from the estimates of the Global Warming Potential.

Additional sets of parameters were estimated or borrowed from the literature. Because of the lack of data or references on robust econometric specifications, we assumed moderate values for energy elasticities. The elasticity of substitution between different energy sources in the energy composite was set to be 0.5. Elasticity of substitution between alcohol and gasoline, however, was set to unity (1) given the increasing number of vehicles with “flex-fuel” technology in Brazil (see Freitas and Kaneko 2011, Santos 2013, and Orrelano et. al. 2013 for empirical evidence). Finally, the elasticities of substitution between technologies in the technology bundle sectors were based on values borrowed from Li et al. (2000) and adapted to the reality of the Brazilian energy matrix. The sensitivity analysis performed on the parameters and elasticities revealed that the results are robust for most variables, considering the methodological specification[13]. Both the detailed parameters values and the sensitivity analysis are provided as supplemental materials.

### 3.2. Simulation design

In this study, we analyze the macroeconomic and environmental impacts of two main energy policies in Brazil by 2026: increased efficiency in energy production and consumption (*efficiency gain*) and a compositional change in the electric grid (*compositional change*). These two energy policies have been widely discussed as part of the official governmental actions and mitigation plans to curb GHG in Brazil. We use a simulation design closely aligned with the

[13] The systematic sensitivity analysis used in our model follows the Gaussian quadrature method proposed by DeVuyst and Preckel (1997). In this method, the CGE model is treated as a problem of numerical integration where the model solution (the equilibrium values for the endogenous variables) and the first moments (mean and variance) can be obtained simultaneously, given the distribution of the exogenous variables (parameters or shocks). These solutions are obtained using Monte Carlo simulations, producing averages, standard deviations, and confidence intervals, providing guidance for how sensitive results are for specific parameters or set of parameters and what parameters have higher impacts on equilibrium solutions.

perspectives and estimates from the Decennial Energy Plan 2026, produced by Brazilian Company of Energy Research – Ministry of Mining and Energy (EPE, 2015).

### 3.2.1. The scenario of increased energy efficiency

We define energy efficiency as the relation between the quantity of a good or service and the amount of energy inputs used for its production (Brookes 2000). Saved energy values are then estimated as the difference between the expected energy consumption under the enhanced energy efficient production and consumption, and the energy consumption if technological standards remained the same as the base year of our simulation – 2005 (EPE 2011).

The estimates of how energy use will change from 2016 to 2026 were obtained from the sectorial projections of energy conservation indicators. These indicators represent the expected change in efficiency of intermediate consumption of electric and non-electric energy sources, in addition to the expected increase in efficient household energy consumption. We interpret increase in energy efficiency as a technological change, where improvements in energy efficiency translate into increased production for a fixed amount of energy used. These technological changes in the intermediate and final (household) energy consumption are our analogs for increased energy efficiency as an energy policy shock.

We adjusted the BeGreen economic sectors to make them comparable with the ones provided by the Brazilian Company for Energy Research – the responsible for projecting the sectorial gains in energy efficiency in Brazil. By 2026, electric energy sources are expected to experience an 4.1% increase in efficiency, compared to an 5.9% increase for non-electric (fuel) sources. Table 4 shows the efficiency gains disaggregated by energy source (electric and non-electric) and sectors used in our CGE model. For the residential sector efficiency gains are expected to be lower (5.81% for electric sources and 8.10% for non-electric sources).

Table 4 – Expected Change in Energy Conservation by Sector (Electric and Non-Electric Energy Sources)*

| Sectors | Electricity Conservation (cumulative change %) | Non-Electricity Conservation (cumulative change %) |
|---|---|---|
| | 2017-2026 | |
| Agriculture and livestock | 2.58 | 4.67 |
| Industry | 3.44 | 5.43 |
| Transportation | 3.61 | 6.66 |
| Commerce and services | 4.60 | 5.45 |
| Residential | 3.76 | 4.29 |

Source: Author's elaboration based on the Decennial Plan on Energy Efficiency 2026.
*Obs.: Electric conservation is applicable to the following energy goods: self-generating hydroelectric energy, self-generating thermal energy, and electric energy distribution. Non-electric conservation applies to wood, charcoal, metallurgical coal, mineral coal, sugarcane bagasse, liquefied petroleum gas, gas, fuel oil, diesel, mineral oil, coke, alcohol, uranium, and natural gas.

A particularly important aspect of energy efficiency refers to the economic cost of adopting a more efficient technology. Since these costs would have a likely negative overall impact on the main macroeconomic variables, our results can be interpreted as a best-case scenario (or the upper bound) for the economic impacts of increased energy efficiency. This assumption is less problematic, since many public policies to foster energy efficiency are already in place in Brazil. Examples of such policies include the Brazilian Program on Labeling, the Brazilian Program for Electric Energy Conservation (ELETROBRAS 2012), and the Brazilian Program on Rational Use of Products Made from Petroleum and Natural Gas (PNEF 2011). As a result, these changes in energy efficiency are part of the current sectorial costs and strategies, reducing the remaining costs expected to be faced in the future (Magalhães and Domingues 2016).

### 3.2.2. The scenario of a compositional change in the electric grid

The scenario of a compositional shift in the Brazilian electric grid was performed in close alignment with the parameters from the Decennial Energy Plan 2026 (EPE 2017). One important difference between our simulation and others worldwide (Sovacool 2009; Mason et al. 2010; Hart and Jacobson 2011; Jacobson et al. 2015, 2016) is that hydroelectric power generation is expected to decrease in importance in the future. While countries like the United States source a small share of its energy supply from hydroelectric power, the latter currently represents 64% of the Brazilian electric grid. Therefore, although most studies simulate an inflated WWS grid, our scenario is more correctly labelled as an inflated WS[14] (wind-sunlight) grid.

Table 5 shows the current and expected change in the share of electric sources in Brazil. The share of hydroelectric sources is expected to decline 8.4 percent points (-13.9%), while wind power is likely to increase 7.2 percent points (105.9%) by 2026[15]. This dramatic increase will move wind power from the least to the second most relevant single electric energy source in Brazil, in tandem with official estimates of a 300 GW potential for energy generation from wind in Brazil (Simas and Paccas 2013). It also reflects two other important features of the Brazilian energy grid: the declining costs of wind towers and turbines, and the possibility to have the energy sourced from wind turbines stored in the hydroelectric reservoirs – an appealing feature of the Brazilian electric grid that prevents the use of thermoelectric power plants (Carvalho 2012).

We define the compositional shock in BeGreen as the annual percent change in the productivity of each electric source required to meet the projected change in the electric energy matrix by 2026. The introduction of costs of clean energy production faces two main challenges. First, the costs estimates of adopting these technologies are not precise in the Brazilian case. Computing appropriately its economic costs would require detailed information on sectors and energy goods related to these new technologies. Second, there are methodological issues for exogenously introducing these costs in a traditional CGE model.

[14] In our simulation design, expansion of sunlight supply will be provided by the households, supposed to install photovoltaic panels privately. That is, increase in solar energy is not part of the future Brazilian energy grid, but its increase in demand will be fulfilled by the households.

[15] From 2013 to 2016, wind power experienced an annual average increase of 90%. Thus, the projected figures given by the Decennial Energy Plan is likely to be conservative, given the recent trend observed in the Brazilian electric grid.

In a response to previous suggestions from experts in the area, we included a type of specification that incorporates the economic costs of investment in technologies to increase the production clean energy. Due to the difficulties explained above, these results are presented only as another scenario, not as definite estimates of the trajectory of macroeconomics aggregates and CO2 emission under the different scenarios.

**Table 5 – Current and Expected Composition of the Brazilian Electric Grid (Relative Share - %)**

| **Electric Source** | **2016** | **2026** |
|---|---:|---:|
| Hydroelectric | 60.4% | 52.0% |
| Thermal | 15.5% | 13.0% |
| Wind | 6.8% | 14.0% |
| Solar, others, and imported | 17.3% | 21.0% |

Source: Authors' elaboration based on premises and projected values from the Brazilian Decennial Electric Plan 2024 (EPE 2017)

### 3.2.3. The baseline scenario ("business-as-usual")

Our baseline scenario represents the evolution of the Brazilian economy from 2006 to 2026 if no energy policy were implemented. The evolution of the economy for the period 2006-2016 is based on the observed scenario of GDP growth, household consumption, government spending, aggregate investments, and exports provided by the Brazilian Institute of Geography and Statistics (IBGE 2016). The baseline $CO_2$-e emissions are based on the observed emissions between 2006 and 2012, provided by the Second Brazilian National Inventory of Emission (Brazil 2014). The future trajectory of the Brazilian economy covering the period 2017-2026 is anchored in the average annual economic growth rate of 2.35% projected by the Brazilian Central Bank (BCC 2016). Given the solution form of the Johansen-type EGC models, the effect of any shock – such as the energy policies tested in this study, is independent of the baseline scenario if the closures rules are correctly formulated.

## 4. Results

Based on our BeGreen model, we estimate how changing the current Brazilian energy grid would impact the country's main macroeconomic variables and GHG emissions (both total and sectorial) under three different scenarios: (S1) "business-as-usual"; (S2) increased energy efficiency in production and in household energy demand (*efficiency gain*); and, (S3) increased share of wind and solar energy sources (*compositional change*). The economic impacts are computed for the following aggregate variables: GDP, household consumption, imports, exports, investments, price, and employment. We also compute the expected change in household consumption by income decile and in the share of household expenditure on energy goods under the different scenarios. These figures allow us to estimate how much a typical household would save due to energy policy decisions. Finally, we measure the change in welfare through the utility index and calculate how much $CO_2$-e emission would be avoided (or released in the atmosphere) depending on the energy policy pursued. This change in emissions is our analog for the environmental impact of these policies. All results are reported as aggregate figures by 2026[16].

The S1 scenario represents the economic trajectory of the Brazilian economy until 2026 if no energy policy would be implemented. This scenario would trace the macroeconomic variables and the $CO_2$-e emissions based on official projections for economic and population growth provided by the Brazilian Central Bank and the Brazilian Institute of Geography and Statistics, respectively. All the results shown in this study must be interpreted as deviations from S1, that is, compared to a situation where no energy policy is implemented. The economic impacts of the energy policies are reflected in the final price of the products consumed by the families, in the

[16] Since BeGreen is a recursive CGE model, it is possible to report cumulative results for shorter periods, like quinquennial or decennial intervals. These results are available upon authors' request.

altered costs of energy generation, and in the input prices for the electric-intensive economic sectors. The macroeconomic variables will capture those impacts by aggregation.

A note on how an energy policy may trigger dynamic economic impacts is important, since this is an intricate mechanism involving simultaneous forces acting sometimes in the same direction, sometimes in opposite directions. Implied by the causality mechanisms set up in the BeGreen model, an increase in energy efficiency reduces the unit costs of production. This effect can be interpreted as a decline in the energy price, likely triggering an implicit reduction in the production costs or in the effective product prices. Intuitively, a change in the relative share of energy generation sources reflects the declining costs of incipient technologies. Although innovation costs have an upward trajectory in the initial stages of production, they tend to decline as new production techniques and new products emerge. This technological effect on prices may affect household consumption and exports directly. Improvements in energy efficiency also reduce the amount of energy inputs per unit product, which may alleviate pressure on the use of primary factors, such as capital and labor. The net effect of these forces, along with other forces (such as the possibility of substitution between energy sources, the sectorial costs structure, and the magnitude of the changes in the sectors directly affected) will determine the *intensity* and the *direction* of the economic impacts on each sector and on household consumption.

**Preliminary Results and Conclusions**

The Brazilian National Energy Plan (NEP) 2030, proposed in 2007, was revised in 2014 with updated guidelines for 2050. The very NEP updating reflects important changes since 2006 for the future of the Brazilian energy sector, including the prolonged effect of the 2008 crisis, the growing concern with climate change, gains in input efficiency in Brazil (including increased efficiency of wind power), the impact of recent nuclear disasters (Fukushima) on the nuclear energy sector, and the challenge of recent droughts on water security. In this setting, normative barriers have been progressively dismantled, with propositions of increased participation of wind and solar energy production, change in household energy consumption behavior (despite projected population increase until 2050), and incorporation of greener technologies in the industry, commercial buildings, and transportation.

Under the scenario of increased nominal demand for energy, coupled with technological and normative potential for greener solutions, the economic gains and GHG benefit of alternative paths to a greener economy are largely unknown. Compared to S1, S2 projects a cumulated gain in efficiency for electric energy sources of 8.5%, followed by gains of about 11.3% for non-electric (fuel) energy from 2011 to 2030. S3 projects increased share of wind power from 4.1% in 2014 to 20% in 2030 (with declining share of hydroelectric power and slightly increased share of thermal power to respond to increased economic activity). Also, under S3 households increase their use of solar panels, with a decline in 13% in electric energy demand until 2030.

In terms of environmental benefits, GHG stock would increase at a slower annual rate under S2 (approximately 2.8% lower than S3). The economic impacts in 2015 are virtually inexistent, with real gains on GNP and household consumption under S2 and S3 of less than 0.10%. In 2030, however, S2 would lead to a GNP increase of 1.62% (against 0.11% under S3). The economic gains would be even higher for household consumption (1.89% under S2 against 0.13% under S3). In terms of disaggregated impact by macroeconomic compounds, both scenarios reveal larger gains for household consumption and trade of balance, suggesting that more efficient and greener energy grid would lead to better macroeconomic foundations. Furthermore, none of these scenarios would lead to inflation in the projected horizon. If we look at economic benefits for households along the income distribution, S2 would represent relative higher gains for the richer families, while S3 would benefit more directly the poorer households. These findings reinforce the classical trade-off between economic efficiency and equity, suggesting that a path of low inflation and equitable growth can be achieved within a greener economy framework.

## Figures and Tables

**Table 1** Macroeconomic Impacts of Increased Energy Efficiency and Compositional Change in the Electric Energy Grid (%Δ in 2030 - Cumulative deviation from the business-as-usual scenario)

| **Macroeconomic compounds** | **Scenarios of Greener Energy System compared to the baseline scenario (cumulative percentage change in 2030)** | |
|---|---|---|
| | Efficiency Gain (S2) | Compositional Change (S3) |
| Real GDP | 1.10 | 0.45 |
| Household consumption | 1.21 | 0.49 |
| Investment | 0.11 | 0.05 |
| Exports | 1.23 | 0.42 |
| Imports | -0.82 | -0.88 |
| Employ | 0.78 | 0.28 |
| Consumer Price Index | -1.61 | -0.50 |

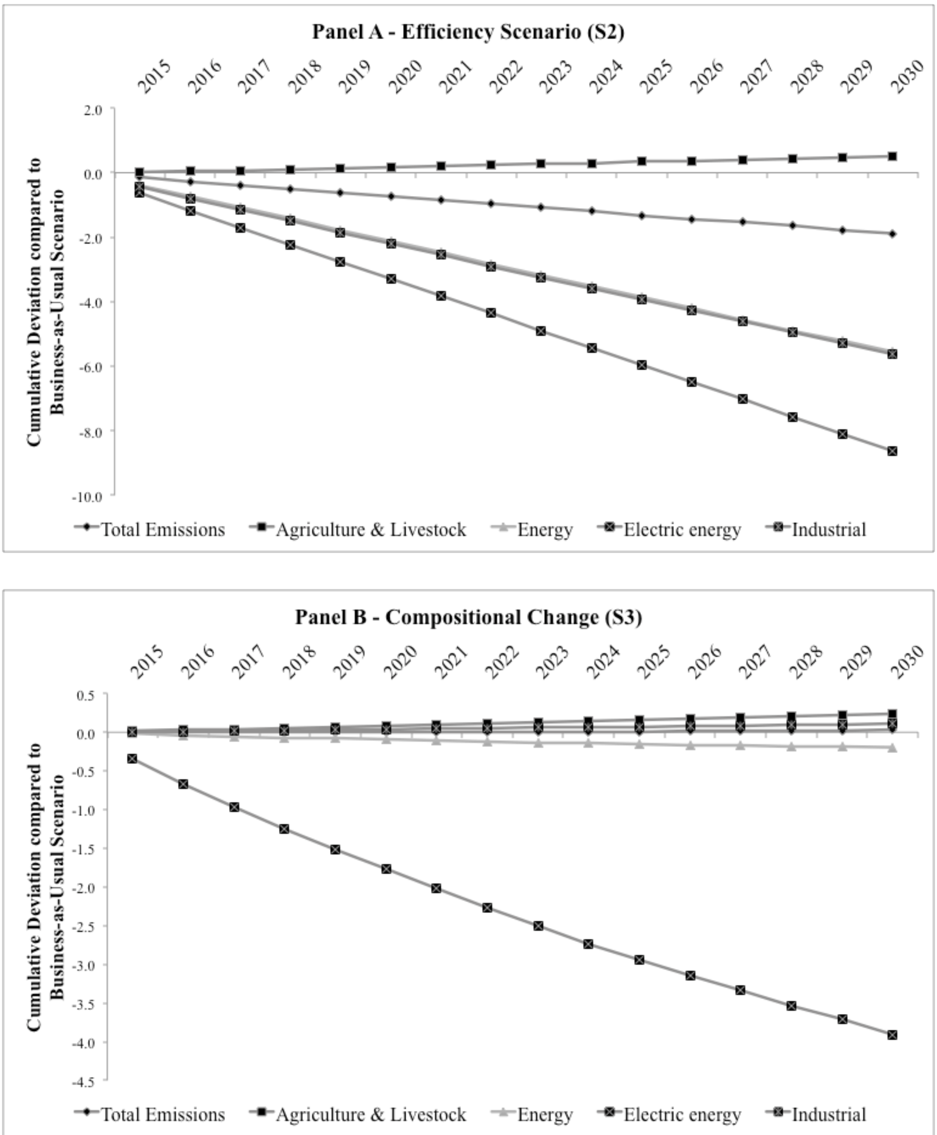
Source: authors’ calculations based on the results of BeGreen model.

**Table 2** Impacts of Increased Energy Efficiency and Compositional Change in the Electric Energy Grid on Household Consumption (%Δ in 2030 - Cumulative deviation from the business-as-usual scenario)

| **Household Decile** | **Scenarios of Greener Energy System compared to the baseline scenario (cumulative percentage change in 2030)** | |
|---|---|---|
| | Efficiency Gain (S2) | Compositional Change (S3) |
| D1 | 0.76 | 0.17 |
| D2 | 0.84 | 0.31 |
| D3 | 0.80 | 0.26 |
| D4 | 0.81 | 0.24 |
| D5 | 0.83 | 0.25 |
| D6 | 0.84 | 0.25 |
| D7 | 0.88 | 0.22 |
| D8 | 0.94 | 0.19 |
| D9 | 1.01 | 0.16 |
| D10 | 1.11 | 0.08 |

Source: Authors' calculations based on the results of BeGreen model.

**Figure 1** Simulated Impact of Different Energy Matrix Scenarios on Greenhouse Gas Emissions by Sectors (%Δ in 2030 - Cumulative deviation from the business-as-usual scenario)




Source: Authors' calculations based on the results of BeGreen model.

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