Heterogeneous welfare and emission effects of energy tax policies in Brazil

Abstract

The consolidation of the energy sector as one of the main emitters of greenhouse gases in Brazil is directly related to the expansion of fuel consumption in passenger and cargo transport and to the higher use of thermal power plants for electricity generation. This fact reflects a detachment from the historical renewable energy and biofuels production and goes against the global efforts to reduce GHG emissions. Our paper analyzes the short-run emissions and distributional effects of energy price changes in a partial equilibrium framework. Our findings suggest that taxes and subsidies in fuel prices (oil and diesel, respectively) are progressive, but have positive impact on total household emissions due to substitution effects. Despite being regressive, changes in electricity price have large effects on household emissions due to the characteristics of electric energy supply in Brazil. More environment-friendly policies that subsidizes ethanol have a small but positive effect on the economy and tends to reduce households emissions. However, large substitution effects - due to an increase in the demand for CO2eq intensive goods, such as commuting and transportation services - when also taxing oil do not offset the reduction in emissions caused by a lower ethanol price. Therefore, understanding who benefits from energy price taxes and subsidies and their welfare impacts policies are key to gaining public support for a greener energy matrix.

Keywords: energy policies, CO_2eq emissions, households.

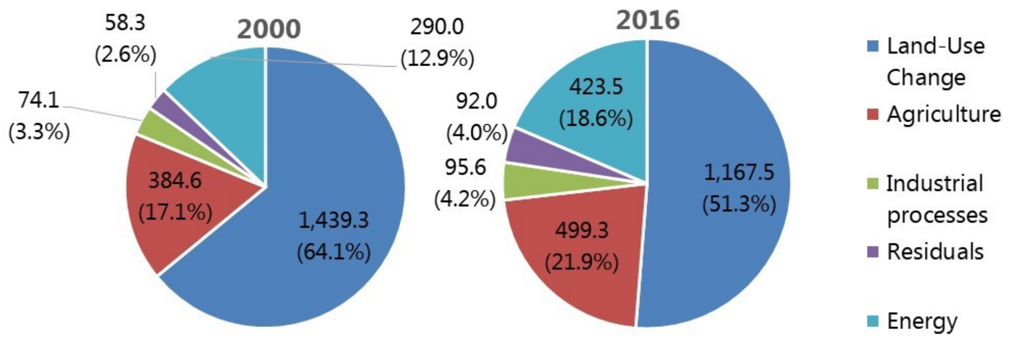
1 Introduction

The activities related to land-use change and agriculture have historically been characterized as the main source of greenhouse gas (GHG) emissions in Brazil. However, over the last years, energy-related GHG emissions increased sharply: from 290 million tons of carbon dioxide equivalent (MtCO_2e), or 12.9% of total emissions in 2000, to 423.5 MtCO_2e, or 18.6% of Brazilian emissions in 2016[1], according to the System Study Greenhouse Gas Emissions Estimates (SEEG), from Climate Observatory Initiative (Figure 1). Thus, total emissions from energy sector are almost equivalent to the total emissions from the agricultural sector (499.3 MtCO_2e or 21.9% of total emissions), being characterized as Brazil's fastest growing emission source[2].

[1] Latest data available. The share is still lower when compared to the majority of the countries.

[2] The methodological approach adopted by SEEG to estimate GHG is based on the IPCC guidelines for national inventories and does not account for GHG removals (gross GHG emissions) and

Figure 1: Evolution of GHG ($MtCO_2eq$) emission in Brazil (2000-2016), by sector



Source: Data from SEEG. Prepared by the author.

As show in Figure 2, the most significant changes in the GHG emission from the energy sector occurred after 2007/08, with the expansion of gasoline and diesel consumption in substitution of alternative fuels both in passengers and freight transportation, as well as the growing use of thermal power plants for electricity generation, mainly for households. In this period, subsidies for fossil fuels and carbon-intensive sectors were used to curb inflation, which made Brazil one of the countries with the highest levels of fossil fuel subsidies in value - R$ 11.6 billion, equivalent to USD 4.9 billion, in 2015 values (Bast et al., 2015)[3]. This approach resulted in artificially low prices to the final consumer for diesel oil, gasoline and electricity from natural gas.

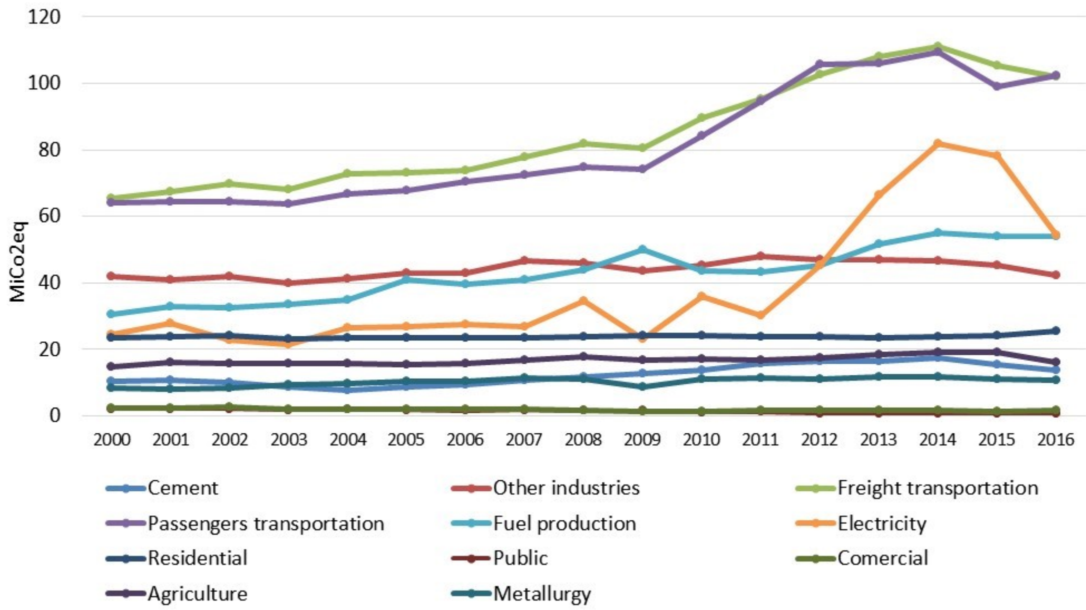
In Brazil, cargo transportation is predominantly done via roads - modality that emits four times more CO_2 than railways and five times more than the waterways (OBSERVATÓRIO, 2016) - using diesel as fuel; for passengers, given the prevalence of flex-fuel cars, the national demand for ethanol has become highly sensitive to changes in prices at the pump; more than 98% of the population is connected to the electricity network and electricity is primarily produced from hydropower, with an increasing share coming from natural gas and coal. Therefore, the recent pattern indicates a more intense use of fossil fuels in the Brazilian energy matrix and a detachment from the historical renewable energy and biofuels production, a pattern

the offsets from GHG emission-reduction certificates originated by Clean Development Mechanism (CDM) projects in Brazil.

[3]According to the authors, Brazil's subsidies to fossil fuels cover mostly oil and gas production and supply, and include RD investments, drilling and fuel transport, as well as power generation by SUDENE - a development agency for the Northeast of the country, responsible for most subsidies to the energy sector. Other national and state development banks and agencies also subsidize the oil industry, such as BNDES, SUDAM and BNB. Investments in refining, transport and marketing by Petrobras has reached USD 7.5 billion in 2014 alone. Investments by Petrobras in Brazil, during 2013-2014 added up to USD 41.6 billion.

that goes against the global trend and the recent international commitments made by government[4].

Figure 2: Evolution of GHG (MtCO_2e) emission from energy sector (2000-2016), Brazil



Source: Data from SEEG. Prepared by the author.

The impact of energy policies has been extensively analyzed under the efficiency focus. The common theme in energy market failures is that energy prices do not reflect the true marginal social cost of energy consumption, either through environmental externalities or average cost pricing. If energy prices do not internalize these externalities, the market will provide a level of energy efficiency that is too low from a societal point of view. The economically optimal policy response is to price emissions, which will indirectly stimulate greater energy efficiency. If policy is absent, an environmental externality leads to an overuse of energy relative to the social optimum, and hence, an underinvestment in energy efficiency and conservation (Gillingham, Newell, and Palmer, 2009). However, the equity aspect, that is, the distributional and welfare effects of changes in the price of energy goods, has received much less attention. This is an important shortcoming since energy tax policies are often accompanied by equity considerations and, in Brazil, nearly 1/4 of the population still lives below the official poverty line (Instituto Brasileiro de Geografia e Estatística (IBGE, 2017)). Findings from previous studies vary according to the energy good that is taxed or subsidized, as well as social and climatic characteristics of jurisdictions in which they are implemented (Pizer and Sexton,

[4]Such as the Intended Nationally Determined Contribution Towards Achieving the Objective of the United Nations Framework Convention on Climate Change (iNDC-Br 2015).

2017).

As a general rule, while there may be some slight regressivity [5] in some high-income countries, fuel taxation is a progressive policy particularly in low- and middle-income countries, where transport fuel taxation can be considered a 'luxury tax'[6] . Sterner (2012)[7] and Granado, Coady, and Gillingham (2012)[8] presents a collection of country case studies on the impact of transport fuel taxes and subsidies on the poor. In their compilation, fuel subsidies are a costly approach to protecting the poor due to substantial benefit leakage to higher income groups. In absolute terms, the top income quintile captures six times more in subsidies than the bottom (Granado, Coady, and Gillingham, 2012). The heterogeneous effects of taxes on transport fuels across countries appears to be due to different usage of cars by different income groups and the availability of public transport. In developing countries, poorer households may be less likely to own a car and, therefore, spend a very small share of their money on fuel for transport. In India, for example, transport fuel expenditure amounts to less than 2% of total income for the lowest income decile and 8% of total income for the wealthiest income decile (Morris and Sterner, 2013). Lack of public transport may, however, lead to regressive effects of taxes on transport fuels.

Beyond transport fuels, Flues and Thomas (2015)[9], Pizer and Sexton (2017)[10], and Cottrell and Falcão (2018)[11] extend the analysis of the distributional impact of taxes and subsidies to electricity and other energy goods. Their findings suggest that, in developing countries, where electrification rates are relatively low, or where energy-consuming durable goods are beyond the reach of poor households, electricity taxes tend to be progressive. However, as incomes grow, and households are connected to the grid, electricity taxes are likely to have a higher impact on mid and low-income households. These households may be cash- and credit constrained so it is more difficult for them to replace old appliances with newer ones even though that would save them money over time. When buying new, the same constraints

[5] The essential idea behind the definition of distributional or heterogeneous effects of a given tax are that taxing a good that is used mainly by the rich is progressive while taxing a good used predominantly by the poor is regressive. In the literature, the budget share is the most commom metric used to assess these effects.

[6] Luxury tax are ad valorem tax or progressive tax charged on high priced goods deemed non-essential.

[7] The author compiled evidence from US, Costa Rica, Mexico, China, India, Indonesia, Ethiopia, Ghana, Kenya, Mali, South Africa, Tanzania, Europe, Czech Republic and Iran.

[8] The review covers estimates of welfare impacts for twenty developing countries from Africa, Asia, the Middle East, and Latin America.

[9] The authors used evidence from 21 OECD countries.

[10] The study used data from Mexico, UK and the US.

[11] The authors compiled results from studies focusing on developing countries.

prevent them from investing heavily in energy efficiency. Therefore, regressivity of electricity taxes may be exacerbated if poorer households live in older, less efficient housing and use less efficient household appliances.

The heterogeneous effects of energy taxes and subsidies in these studies are mainly assessed in monetary terms, by measuring the changes on expenditures and income as tax burdens and variations in welfare. To the best of our knowledge, few studies extend the analysis to heterogeneous environmental impacts at the household level. The recent studies for Mexico (Renner, Lay, and Greve, 2018) and Indonesia (Renner, Lay, and Schleicher, 2017) simulate stylized price-increase scenarios for several energy goods. The findings from the former paper indicate that, despite of not having the highest carbon intensity, a motor-fuel price increase/tax would create the largest emission reductions, driven by relatively large budget shares. Emission reductions through electricity price changes would also be large, determined by high price elasticities despite relatively small budget shares. Remarkably, taxing gas alone has no observable effect on CO_2 emissions. This seemingly counter-intuitive result can be explained by positive cross-price elasticities with electricity. As a clear substitute and with higher carbon intensity, increased electricity demand turns the emission saving from reduced gas use into a small net emission increase. For the latter, moderate price changes for electricity and gasoline lead to substantial emission reductions of household carbon emissions, due to the high carbon intensity of electricity and high budget shares for gasoline. The results related to distributional effects of both studies are also aligned with the previous literature.

Previous studies from Brazil have mainly only focused on the relationship between household income and consumption growth and total (direct plus indirect) energy requirements and emissions. Cohen, Lenzen, and Schaeffer (2005) used a generalized input–output model to calculate the energy embodied in goods and services purchased by households of different income level in 11 capital cities of Brazil. The findings show that the total energy intensity of household expenditure increases with income level, but there is a considerable spread in energy intensities within income classes as well as disparities between regions of the country. Perobelli, Faria, and Almeida Vale (2015) extended the analysis of Cohen, Lenzen, and Schaeffer (2005) by associating energy requirements to emissions. The authors also used an input-output model to analyze how household consumption affects the setorial output of emissions in the Brazilian economy. They found that higher income levels are also responsible for the largest share of total emissions in the country and emissions generated by the transportation and food sector, for example, are positively and negatively correlated with income, respectively.

This study aims to asses the heterogeneous welfare and emission impacts of energy price changes for Brazilian households. As a reference, we use recent taxes and subsidies implemented by the government on motor fuels, electricity and white appliances[12], as well as alternative tax policies, which are considered more environment-friendly and, in theory, tend to reduce GHG emissions. Our estimation strategy first comprises the estimation of carbon dioxide equivalent (CO_2eq) emission coefficient due to fossil fuel for goods/services consumed by households, also known as carbon footprints, followed by the estimation of price and income elasticities derived from a censored consumer-demand system. Brazil provides an interesting case-study since it has the largest fleet of flex-fuel vehicles in the world, which allows the final consumer to choose between a fossil (gas) or a renewable fuel (ethanol).

Based on this background, we contribute to the literature in two ways. First, by identifying the policies with greater cost-effectiveness in terms of welfare and CO_2eq emissions in Brazil, and second, by using a censored energy consumer demand system. This methodology has been largely applied in food-demand contexts (Yen, Kan, and Su, 2002) but it is still incipient for energy demand[13].

Our findings suggest that short-run emission and welfare effects at the household level can be substantial, depending on the policy. Taxes and subsidies in fuel prices (oil and diesel, respectively) are progressive, but have positive impact on total household emissions due to substitution effects. Despite being regressive, changes in electricity price have large effects on household emissions due to the characteristics of electric energy supply in Brazil. Alternative policies that subsidizes ethanol have a small but positive effect on the economy and tends to reduce households emissions. However, large substitution effects - due to an increase in the demand for CO2eq intensive goods, such as commuting and transportation services - when also taxing oil do not offset the reduction in emissions caused by a lower ethanol price. Policies that promote a more efficient use of electricity are regressive and increase households carbon footprints.

Following this section, We present an overview of the recent energy tax policies implemented in Brazil, the estimation strategy (Section 3) and data sources (Section 4). Sections 5 and 6 present the discussion of the results and conclusions.

[12] Brazilian energy tax structure did not undergo through significant changes in this period.

[13] To the best of our knowledge, the only study which also adopted this methodology was Renner, Lay, and Schleicher, 2017.

2 Background: Energy tax policies affecting households

Over the past decades, the government had an important role in designing the country's energy supply. The strategy developed during the seventies to replace imported fossil energy with renewable sources such as hydro power and biomass largely contributed to the current profile of the Brazilian energy matrix. However, the adoption of structural adjustment policies during in the last two decades deteriorated the sustainability of the country's energy supply mix.

In 1973, the first oil shock caught Brazil with barely 17% of its oil needs met by domestic production. After the second oil shock in 1979-80, the oil bill amounted to the financial equivalent of more than half of Brazilian exports (La Rovere and Simões, 2008). In response to rising costs of oil imports and motivated by the goals of saving foreign exchange, increasing rural incomes in sugarcane producing areas and stimulating industrial growth, the National Alcohol Programme (PROALCOOL) started in the early 1970s, together with the acceleration of large hydropower plants construction. These policy objectives were also pursued by taxing gasoline and diesel and subsidizing other petroleum products - such as natural gas (Hira and De Oliveira, 2009; Khanna, Nuñez, and Zilberman, 2014). Since the program required that alcohol eventually replace gasoline as a transportation fuel for the automobiles, the government also provided incentives for automobile manufacturers to develop vehicles capable of running on ethanol.

As pointed out by La Rovere and Simões (2008), during the 1980s, the economic picture deteriorated progressively with snowballing foreign debt and high inflation rates contributing to a decade of economic recession. Government deficits and negative balance of payments meant that the government no longer had the capacity to maintain the same energy policy. The declining oil prices (gasoline prices) combined with rising sugar prices and the removal of government subsidies decreased the incentive for consumers to buy ethanol-powered cars, as well as the interest of the auto industry in producing them. As a consequence, the PROALCOOL ended in 1991.

The 1988 Constitution is an important milestone to the Brazilian energy tax structure. It conferred the authority to tax electricity and fossil fuel to States (article 155, § 3o). The tax on Circulation of Goods and Services (ICMS) became an an essential source of tax revenue to the States[14]. Federal jurisdiction was maintained

[14] The distribution of financial resources among the Brazilian states occurs as following: the state which produces electricity derived from hydraulic potential receives royalties while the state which

for the import and export taxes and contributions (contributions to the Social Integration Plan (PIS), to the Public Server Patrimony Formation Program (Pasep), to the Social Security Financing (COFINS) and to the intervention in the Economic Domain (Cide-Combustíveis)[15], which are mainly characterized as an ad valorem taxes [16].

During the 1990s, reforms in the energy sector were introduced to establish a legal and regulatory framework, liberalize oil exploration and production, induce foreign private investment and reduce the monopoly power of the state-controlled company, Petrobras (Law No. 9.478/1997, the Petroleum Law). Subsidies for petroleum products were phased out. Rounds of privatization were carried out in the electricity sector, which led to the establishment of the National Electric Energy Agency (ANEEL) that regulates prices and electricity generation.

In early 2000s, significant changes in the Brazilian hydrological cycle drastically reduced the share of electricity generated by hydropower. The scarcity of rain decreased the volumes in the reservoirs of the hydroelectric power plants located mainly in the Southeast, Center-West and Northeast regions. The government introduced regulations that forced electricity generating companies to ration its supplied electricity and to compensate the demand with costlier thermal power fuelled by natural gas, biomass and coal, which increased electricity generating price (Frodeman, Klein, and Pacheco, 2017). At the same time, bioethanol production in Brazil started to grow at unprecedented rates, prompted by the introduction of flex-fuel vehicles (running on ethanol, gasoline, or any combination of the two) and the government strategic decision to incentive ethanol exports, since the demand was growing in Europe and the US.

The escalation of the international oil price, as a consequence of the 2007/08 economic crisis, together with the identification of large domestic offshore oil reserves radically changed the perception of the Brazilian oil situation. Price subsidies for petroleum products were reintroduced to minimize the effect of the oil price escalation, which led to significant losses for the state-owned oil producer and encouraged flex-fuel vehicle owners to choose the fossil option over ethanol (De Oliveira and Laan, 2010). Several other policies to foment economic growth were also adopted: credit facilitation to households, increase of the distribution of cash grants to the

consumes this energy is remunerated with ICMS levied on electric energy. The same structure applies to trade in petroleum-derived fuels.

[15]Cide-Combustíveis is a Federal tax instrument used for regulating the fossil fuel market.

[16]The coexistence of state and federal ad valorem taxes provides high complexity to the tax system. Despite the fact that the incidence of the tax occurs in the production chain, the economic agents obviously pass on the tax burden to the final consumer, increasing the final energy price and the price of other goods that depend on it for its production.

poor and reduction of taxes and customs duties for consumer-oriented industries, such as automakers and white-good manufacturers. For the latter, Brazilian government exempted taxpayers from Tax on Industrialized Products (IPI), through the Decrees No 7.878/2012 and No 8.035/2013 [17]. As a result, there was a sharp increase in the purchase of home appliances and equipment such as computers, mobile phones, refrigerators, TVs and air-conditioning sets, which tend to be more energy-efficient than old appliances.

After the recover of the electric supply capacity, new regulations were introduced by the government aiming at the expansion and diversification of its capacity, as well as the implementation of subsidies to boost competitiveness and economic growth. A law to that effect (Law No 12.783/2013) was passed in January 2013, which led to a reduction in electricity prices by 18% for domestic consumers and 32% for industry. Since 2015, electricity bills are based on tariff flags, in which the color used is responsible for indicating generation costs. The main purpose is to aware each consumer when electricity price is higher, motivating reduction in energy consumption.

Overall, Brazil's energy mix is becoming more carbon intensive because of increased reliance on fossil fuels, heavy investments in the Pre-Salt oil fields, subsidies to keep gasoline prices artificially low, and tax subsidies that encourage the purchase of new cars, among other reasons. The 2015 economic crisis has forced the government to review some energy tax and subsidy policies, but there are still some uncertainties about their implementation. As an example, after the announcement of diesel tax cuts and subsidies, Brazilian truckers staged a 10-day strike causing shortages of basic goods and a run-out of fuel across the country. The government has agreed to lower diesel prices through a 10% reduction in pump prices. To partially offset the subsidies' cost and to avoid breaking budget rules, the government was expected to cut spending by 3.8 billion reais (USD 1.3-billion) in 2018. There are also unclear rules that reduce the attractiveness of investments in renewable energy, which also leave a lot of opportunities "on the table" (De Oliveira and Laan, 2010).

[17] The changes in tax rates depended on the type of product. For stoves, the reduction was 4%; for washing machines, In the case of washing machines, refrigerators and "tanquinhos", it was 10%.

3 Data and Empirical Strategy

The estimation of the heterogeneous effects of different energy tax and subsidy policies on the household welfare and emissions requires two types of information: (i) the CO_2eq emission coefficient, which indicates how much CO_2eq was generated throughout the production chain of a specific good/service (the carbon footprint) and (ii) price and income elasticities for the respective goods. The methodologies used for the estimation of each group of information are presented below.

3.1 CO_2eq emission coefficients

The most widespread method in literature for evaluating the environmental implications of production and consumption activities is the Hybrid Input-Output (HIO) approach (Druckman et al., 2011b; Thomas and Azevedo, 2013; Chitnis et al., 2014). We follow Guilhoto and Sesso Filho (2005) to build the national input–output matrix for 2010[18], based on the Supply-Use Tables (SUTs) provided by the IBGE, which contains information of production and intermediate consumption, in monetary units, of 128 products and 68 economic sectors.

This approach requires the development of the matrix $\boldsymbol{E}_{exn}$, that represent the energy consumption in the economy and it is expressed in physical units (ton of oil equivalent, toe) of e sources of energy in n economic sectors ($e < n$). The matrix $\boldsymbol{E}$ was build based on information from the Brazilian Energy Balance (BEN, in portuguese acronym), which provides energy requirements (in toes) for 21 economic sectors from 24 energy sources[19]. Since the level of aggregation in both databases is different, the key issue is to reconcile the economic sectors from both databases and then identify which source of energy in BEN is compatible with the goods in SUTs. For this procedure, we follow Montoya, Lopes, and Guilhoto (2014). Then, the matrix $\boldsymbol{E}$ substitutes the intermediary input flows in the energy sectors (matrix $\boldsymbol{Z^*}$), the total production vector ($\boldsymbol{x^*}$) and the final demand vector ($\boldsymbol{y^*}$). It follows that:

$$\boldsymbol{A}^* = \boldsymbol{Z}^*(\hat{\boldsymbol{X}}^*)^{-1} \tag{1}$$

where $\boldsymbol{X^*}$ is a matrix with the elements of $\boldsymbol{x^*}$ on the diagonal and zeros elsewhere and $\boldsymbol{A^*}$ is the technical coefficient matrix in hybrid units.

[18] As presented in the next sections, there is a need to reconcile data from the Brazilian Household Budget Survey, from 2008/2009, and the SUTs. We used data for 2010 since it is the the oldest and most disaggregated information available at the SUTs.

[19] Energy generated by self-producers were not added since the majority of this energy is consumed by the same companies and, therefore, does not generate added value ("Sistema de Contas Nacionais-Brasil Referência 2000").

Subsequently, the energy requirements are converted into CO_2, CH_4 and NO_2[20] and then to CO_2eq based on the energy conversion coefficient for fossil fuels[21] available at the Second Brazilian Inventory of Greenhouse Gas Emissions, that follows the IPCC Guidelines for National Greenhouse Gas Inventories (Change, 2007) as well as the Global Warming Potential (GWP) conversion factors [22]. These conversion coefficients that take into account the characteristics of the chemical process and technology applied to each greenhouse gas. Thus, assuming that CO_2eq emissions by energy use are linearly related to its energy requirements, it is possible to estimate both direct emissions (from intermediary consumption) as well as total emissions (direct and indirect, obtained from the final demand) for each good and economic activity, as suggested by Pereda et al. (2018). In this procedure, first it is calculated the proportion of each product used in the total production of a specific sector:

$$b_{ij} = \frac{u_{ij}}{\sum_i r_{ij}} \tag{2}$$

where u_{ij} is the element ij of the 'use' matrix, denoting the amount of product i used in the production of sector j, and $\sum_i r_{ij}$ is the total production of sector j. Then, the proportion of a sector in the national production of each good through the 'make' matrix is calculated as follows:

$$d_{ij} = \frac{r_{ij}}{\sum_j r_{ij}} \tag{3}$$

where $\boldsymbol{R} = r_{ij}$ is the 'make' matrix for product i in sector j, such that r_{ij} is the amount of i produced by sector j and $\sum_j r_{ij}$ is the total production of good i.

Finally, the technical coefficient input matrix $\boldsymbol{A}_p$, is obtained by the multiplication of $\boldsymbol{B}$ and $\boldsymbol{D}_t$. The coefficients can be interpreted as the quantity of CO_2eq that product i uses to produce one unit of product j (expressed in ton CO_2eq/USD mi, in 2009 values[23]. Direct CO_2eq emission is equivalent to the sum the k lines of

[20] CO_2, CH_4 and NO_2 are the three main long-term drivers of climate change.

[21] The following fuels were considered: natural gas, steam coal, metallurgical coal, diesel oil, fuel oil,gasoline, LPG, kerosene, gas coke, coal coke, other oil by-products, and coal tar.

[22] The "global warming potential" (or "GWP") of a GHG indicates the amount of warming a gas causes over a given period of time (normally 100 years). GWP is an index, with CO_2 having the index value of 1, and the GWP for all other GHGs is the number of times more warming they cause compared to CO_2. E.g. 1kg of methane causes 25 times more warming over a 100 year period compared to 1kg of CO2, and so methane as a GWP of 25.

[23] To reconcile with the Budgetary Household Survey, we converted 2010 values in 2009 values.

$\boldsymbol{A}_p$ that measure emissions:

$$c_{i,CO_2eq} = \sum_k ap_{kj} \tag{4}$$

in which $k \leq i$. Total emissions (direct plus indirect) are calculated by multiplying intermediate consumption coefficients by the Leontief inverse matrix.

3.2 Household demand system

Consumer behavior theory says that individuals choose what and how much to consume to maximize their well-being subject to a budget constraint. If the consumer set of choices is consistent[24], the study of consumer behavior can be performed in a classic optimization problem[25], allowing the estimation of price and income elasticities.

However, consumer theory does not specify the functional forms for the demand equations. The advantage of estimating a system of demand equations instead of equation by equation relies on the joint estimation and empirical tests concerning the validity of the theoretical restrictions implied in the consumer theory. We choose the Quadratic Almost Ideal Demand System (QUAIDS), which considers the non-linearity of income, as presented below:

$$w_i = \alpha_i + \sum_{j=1}^{n} \gamma_{ij} ln(p_j) + \beta_i ln(\frac{m}{a(p)}) + \frac{\lambda_i}{b(p)}[ln(\frac{m}{a(p)})]^2 \tag{5}$$

where w_i is the expenditure of good i, p_j is the price of good n, m is the total expenditure per capita, ln $\alpha(p)$ is the transcendental price index such that:

$$ln[a(p)] = \alpha_0 + \sum_{i}^{n} \alpha_i ln(p_i) + 1/2 \sum_i \sum_j \gamma_{ij} ln(p_i) ln(p_i) \tag{6}$$

and $b(p)$ is the Cobb-Douglas price aggregator, described as:

$$b(p) = \prod_{i=1}^{n} p_i^{\beta_i} \tag{7}$$

and

$$\lambda(p) = \sum_i \lambda_i ln p_i \tag{8}$$

[24]The consistency of preferences implies acceptance of the axioms of reflexivity, completeness, transitivity, continuity, not local satiety and strict convexity (Deaton and Muellbauer, 1980b).

[25]Due to consistency of consumer preferences, the system of demand equations presents the properties of additivity, homogeneity, symmetry and negativity.

The theoretical constraints on the models parameters are:

$$\sum_{i=1}^{N} \alpha_i = 1; \sum_{i=1}^{N} \beta_i = 0; \sum_{i=1}^{N} \lambda_i = 0; \sum_{i=1}^{N} \gamma_{ij} = 0, \forall j \in I \tag{9}$$

$$\sum_{j=1}^{N} \gamma_{ij} = 0, \forall i \in I \tag{10}$$

$$\gamma_{ij} = \gamma_{ji}, \forall i \neq j \tag{11}$$

Following the demographic translation approach by Pollak and Wales (1981), we introduce socio-demographic shifters (z_j) by substituting (12) into (5) and (6) Demographic shifters were used to allow for household heterogeneity:

$$\alpha_i^* = \alpha_i + \sum_{j=1}^{n} \delta_{ij} z_j, \tag{12}$$

This procedure requires one additional constraint to the system of equations ($\sum_{j=1}^{n} \delta_{ij} = 0, \forall i \in 1, ..., n$).

The empirical estimation of a demand system requires household expenditure data. The main source of this type of information is the micro-level data from the Brazilian Household Budget Survey (portuguese acronym, POF), last carried out by IBGE from May, 2008 up to May, 2009. The survey is a cross-sectional nationally representative study that contains data on all household and individual expenses during a given period. Food and beverage expenses are collected for a 7-days period; building materials expenses, rent, taxes are compiled for a 12-month period; expenses related to the consumption of energy foods (electricity and fuels) are collected for a 90-days period, while individual expenses with transportation, education, meals outside the home, medicines, hygiene, health, furniture and vehicle acquisitions varies according to the good/service. In POFs, IBGE provides information for almost 14,000 products, while the most recent and disaggregated data from SUTs presents only 128 products. In order to reconcile both datasets, we used the IBGE official translator to match POFs products according to their similarity with the products available at the SUTs.

The use of household budget survey data for demand system estimation often creates a problem due to the lack of consumption of certain goods during the recall period. This causes censored dependent variables and leads to biased results when not accounted for. Since the seminal work of Heien and Wesseils (1990), several empirical procedures for censored data have been developed such as those suggested by Perali and Chavas (2000) and Shonkwiler and Yen (1999) - which is the main procedure in the literature due to the simplicity of its estimation. Following Shonkwiler and Yen (1999), the demand system of I equations can be written as below:

$$w_{ih}^{*} = f(x_{ih}, \beta_i) + \epsilon_i \tag{13}$$

$$d_{ih}^{*} = z_{ih}'\alpha_i + v_{ih} \tag{14}$$

$$d_{ih} = \begin{cases} 1 & \text{if } d_{ih}^{*} > 0 \\ 0 & \text{if } d_{ih}^{*} \leq 0 \end{cases} \tag{15}$$

$$w_{ih} = d_{ih} w_{ih}^{*} \tag{16}$$

where i and h represents the good and the household index, respectively, d_{it} and w_{it}, are the observed dependent variables (consumption or non-consumption and its respectively budget shares), d_{it}^{*} and w_{it}^{*} are corresponding latent variables (unobserved), x_{it} and z_{ih} are vectors of exogenous variables (the same used in (5)) and ϵ_i and v_{it} are random errors.

The consumption of each good can be characterized as a two-stage decision: the first step corresponds to a probit model with the same variables as the QUAIDS model, in which its cumulative distribution ($\hat{\Phi}$) and the probability density function ($\hat{\phi}$) are used in the second step to augment the QUAIDS estimation:

$$w_{i}^{*} = \hat{\Phi}_i w_i + \hat{\phi}_i \tag{17}$$

In the censored QUAIDS, the deterministic components on the right-hand side of equation set (17) do not add up to unity across all equations of the system in general, and so the error terms in the estimation form do not add up to zero. Thus, the usual procedure of imposing the adding-up restriction (9) on the system and dropping one arbitrary equation is not valid. Therefore, with censoring, the second step of the system (17) is estimated correctly when using the entire set of equation (Yen, Kan, and Su, 2002).

The expenditure (18) and price elasticities (compensated, (19) and uncompensated, (20)) formulas for the non-linear QUAIDS can be expressed as:

$$\eta_i = 1 + \Phi_i / w_i [\beta_i + (\frac{2\lambda_i}{b(p)}) ln(\frac{m}{a(p)})] \tag{18}$$

$$\epsilon_{ij} = -\delta_{ij} + \Phi_i/w_i[\gamma_{ij} - (\beta_i + (\frac{2\lambda_i}{b(p)})ln(\frac{m}{a(p)}))(\alpha_j + \sum_k \gamma_{jk} - lnp_k) - \frac{\lambda_i\beta_i}{b(p)}(ln(\frac{m}{a(p)}))^2 \tag{19}$$

where δ_{ij} is the Kronecker delta (equal to one only for own price elasticities, and zero otherwise).

$$\epsilon_{ij}^{H} = \epsilon_{ij} + (\frac{\beta_i}{w_i} + 1)w_j \tag{20}$$

Elasticities were calculated for the overall sample and among the 20% richest and 20% poorest households in the dataset in order to capture the heterogeneous effects of the energy tax policies. All models were estimated by Feasible Generalized Non-linear Least Squares (FGNLS), and standard errors were computed by non-parametric bootstrap with 500 repetitions. As α_0 is difficult to estimate(Deaton and Muellbauer, 1980b), we follow Boysen (2012) and adopt an arbitrary and low value of 5. Other values did not change the resulting elasticities but caused the procedure to require many more iterations to converge. Robustness checks were also conducted using an uncensored QUAIDS and AIDS models with the STATA procedure suggested by Poi (2012) with the same specification.

3.2.1 Construction of group aggregates and prices

Of particular importance is the choice of categories for grouping household expenditure and the level of aggregation of those categories. After the reconciliation of POF and SUTs datasets, we follow Druckman et al. (2011a) and Schmitz and Madlener (2017) for the aggregation of total household expenditures into nine main categories, which allows the understanding of the consumption dynamics between direct and indirect energy use goods: (i) Food and catering, (ii) Recreation, culture and education, (iii) Clothing and footwear, (iv) Commuting and Transportation, (v) Health and Hygiene, (vi) Energy (Electricity, Gas, Ethanol, Diesel and Coal), (vii) Housing (White appliances), (viii) Other goods and (ix) Other services. Table 1 provides an description of the items included in each of these categories.

The main theoretical variables for household demand system are, basically, total expenditures (proxy for income)[26] and prices, calculated as unit values ($p_i = UV_i$). Particularly for the products from group 1 (Food and catering), there are two main

[26] Since household income is self-reported, this information might be associated with negative report bias. To overcome this issue, the literature usually adopts household total expenditure as a proxy for household income.

Table 1: Description of expenditure groups

Group	Items
1 Food and catering	Food and beverages
2 Recreation, culture and education	Private education, arts, books, hotels
3 Clothing and footwear	Clothes, shoes, fabrics, textiles
4 Commuting and Transportation	Air, water and ground transportation
5 Health and Hygiene	Pharmaceutical products, private health
6 Energy	Electricity, Gas, Ethanol, Diesel and Charcoal
7 Housing	White appliances, rent, water and sewage
8 Other goods	Plastic, ceramic, wood and paper articles
9 Other services	Public and other administrative services

Source: Prepared by the authors.

problems related to the price we calculate from the household expenditures surveys: potential measurement error, and differences in quality and packaging (Boysen, 2012). In this sense, we use a price correction method based on Cox and Wohlgenant (1986)[27], detailed in the section 6.1 (Appendix).

As not all household have positive consumption of all food items, the missing observations has been approximated by the average of $\hat{p}_i$ coefficients over the neighboring region - first, the state and, if it is still missing, the strata. After the price corrections for each food item of group 1, we computed the weighted the price indexes – Stone price index (Deaton and Muellbauer, 1980a); this procedure was also done for the unit values of all items of the other groups (Recreation, culture and education, Clothing and footwear, Commuting and Transportation, Health and Hygiene, Energy, Housing, Other goods and Other services):

$$lnp_g = \sum_{i \epsilon I_g} w_i lnp_i \tag{21}$$

in which I_g is the set of items included in aggregate item group g, p_i is the price and w_i is the budget shares for item i in each household. In the POF, there is a

[27]Deaton (1990) also proposes a procedure to correct unit values, assuming that there are no price variations within a geographic area near the households. The variations observed in unit values for households in a given area are due to quality differentials and measurement errors of the goods previously acquired. That is, for households physically close to each other, the reported price should be the same in a similar period of time. Besides its difficulty of implementation - due to a large matrix multiplication -, the main disadvantage of Deaton's method is that the covariance of the residuals - which is used to estimate corrected price elasticities - can be influenced by many unexplained factors and not just price variation.

limitation related to the lack of specification of the quantity consumed of several goods and services particularly consumed: on a 12-month period (e.g. rent, taxes, construction and reform) and on an individual basis (e.g. education, commuting and transportation), mainly aggregated into groups 2, 4, 5, 7 and 9. To overcome this issue, we assumed that the quantity consumed was equal to 1 for the households with positive consumption of the respective good/service.

Table 2 presents the adjusted and aggregated prices, which can be interpreted as a relative price index: for example, richer households expend 250% and 120% more on commuting and transportation services and energy goods, respectively, when compared to poorer households. In order to disaggregate the groups per different income levels, we used the information of total income as stated in POF. It contains wage, transfers, rental income, non-cash and other incomes.

Table 2: Price Indices by group and income level

Mean / (sd)	All sample	20% richer	20% poorer
Food/Catering (USD/Kg)	10.24	12.23	9.99
	(0.0634)	(0.2340)	(0.0689)
Culture/Education (USD/service)	252.32	528.99	101.57
	(1.9948)	(6.8069)	(1.5455)
Clothing (USD/item)	32.02	40.03	24.37
	(0.1214)	(0.3971)	(0.1523)
Commuting/Transportation (USD/service)	443.54	732.14	207.06
	(3.5823)	(11.1350)	(3.6142)
Health/Hygiene (USD/service)	10.03	14.32	7.02
	(0.0922)	(0.3740)	(0.0480)
Energy (USD/KWh,L)	15.33	22.33	10.16
	(0.0955)	(0.3149)	(0.1131)
Housing (USD/service)	181.25	299.88	106.92
	(1.3238)	(4.5716)	(1.2247)
Other goods (USD/item)	41.95	74.39	17.01
	(0.6399)	(2.0302)	(0.5314)
Other services (USD/service)	130.89	237.49	50.99
	(0.9297)	(2.9435)	(0.9878)

Source: Prepared by the authors. Based on Household Budget Survey (2008/09).

Note: Prices per unit in USD, 2009 values.

The descriptive statistics of socio-economic variables is presented in Table 3, which may help explain the differences in preferences of the families on the products analyzed. Richest households have almost 5 more years of education compared to the 20% poorest households and have houses with a larger number of rooms - a proxy for wealth.

Table 3: Summary statistics: socio-economic characteristics

Mean / (sd)	All sample	20% richest	20% poorest
Education of the household head (years)	7.4	10.6	5.9
	(0.0346)	(0.0719)	(0.0346)
Age of the household head (years)	47.6	49.1	42.6
	(0.1540)	(0.2476)	(0.2173)
Number of bathrooms	1.3	2.8	1.1
	(0.0178)	(0.0250)	(0.0145)
Number of rooms	3.3	7.5	3.1
	(0.0071)	(0.0255)	(0.0096)

Source: Prepared by the authors. Based on Household Budget Survey (2008/09).

Table 4 shows the descriptive statistics of budget shares (in 2009 USD), positive consumption for each of the nine groups and income levels. On average, censoring is higher for health and hygiene products, as well as for culture and private education, mainly because poorer households have a lower consumption of goods from these groups.

Table 4: Budget shares and positive consumption by group/ income level (%)

Mean / (sd)	Budget share			% of positive consumption		
	All sample	20% richer	20% poorer	All sample	20% richer	20% poorer
Food/Catering	15.5%	3.0%	29.9%	70.8%	86.0%	29.3%
	(0.0928)	(0.0762)	(0.2687)			
Culture/Education	5.2%	10.3%	1.8%	26.4%	48.1%	11.1%
	0.0570)	(0.1724)	(0.0795)			
Clothing	23.9%	23.4%	22.1%	75.1%	79.5%	63.4%
	(0.1048)	(0.2256)	(0.2421)			
Commuting/Transportation	8.4%	14.5%	3.6%	37.3%	60.3%	20.7%
	(0.0749)	(0.2003)	(0.1158)			
Health/Hygiene	3.1%	1.4%	3.4%	18.4%	16.9%	10.5%
	(0.0371)	(0.0533)	(0.0914)			
Energy	20.4%	22.5%	14.3%	52.6%	53.6%	41.3%
	(0.1082)	(0.2567)	(0.2168)			
Housing	11.7 %	15.7%	10.2%	80.9%	91.3%	68.7%
	(0.0646)	(0.1755)	(0.1409)			
Other goods	8.2%	3.4%	13.6%	76.2%	47.0%	83.9%
	(0.0597)	(0.0861)	(0.1755)			
Other services	3.6%	6.8%	1.0%	29.9%	41.9%	19.2%
	(0.0443)	(0.1301)	(0.0533)			

Source: Prepared by the authors. Based on Brazilian Household Budget Survey (2008/09).

Other goods: rubber, plastic, ceramic goods, non-metallic minerals, inorganic chemicals.

Other services:development of systems and other information services, private and public administrative services.

Expenditure share of energy goods by different income levels is presented in Table 5. Energy consumption in Brazilian households includes electricity and fuel for cooking (charcoal) and transportation (ethanol, diesel and gasoline). On average, the majority of households expenditures refers to electricity and gasoline consumption. Richer households presents a smaller expenditure share on electricity when compared to poorer households. However, expenditure shares on fuel are smaller for poorer households.

Table 5: Expenditure share of energy goods by income level

Mean / (sd)	All sample	20% richer	20% poorer
Charcoal	0.1%	0.3%	0.2%
	(0.1%)	(0.9%)	(0.2%)
Diesel	2.8%	4.1%	1.1%
	(2.1%)	(0.0%)	(0.0%)
Electricity	61.9%	40.5%	73.4 %
	(20.2%)	(20.5%)	(11.2%)
Ethanol	3.7%	5.2%	1.7%
	(10.4%)	(3.2%)	(0.9%)
Gasoline	42.7%	60.8 %	23.2%
	(30.7%)	(18.1%)	(9.6%)

Source: Prepared by the authors. Based on Household Budget Survey (2008/09).

3.3 Effects of Energy Tax/Subsidy Policies

3.3.1 Simulation: scenarios

Tax and subsidy policies recently implemented to energy goods in Brazil were used as reference for the simulations of this study. In addition, we compare the results of these policies with the potential results of more environment-friendly policies, which promotes the use of cleaner sources of energy and tends to reduce the consumption of fossil fuels. As presented in Table 6, Scenarios 1-4 include subsidy on diesel, subsidy on electricity, tax on oil and subsidy on white appliances. Scenarios 5-8 present the results of a hypothetical tax on diesel, subsidy on ethanol, a tax on fossil fuels (oil and diesel) together with a subsidy on ethanol, as well as a subsidy on white appliances with a tax on electricity. Since taxes and subsidies rates applied to gasoline, ethanol and diesel changed considerably overtime, we used a 10% tariff rate as reference for simulation purposes. Similarly, as tariff rate reduction also varied among white appliances, we also adopted a 10% tariff rate in our calculations. For electricity, we used the rates announced by the Brazilian Government in 2013 - reduction of 18%.

For each of these scenarios, two effects are analyzed: (i) the welfare effects, based on estimation of the compensated variation and tax burden, and (ii) emission effects, both explained below. To assess distributional differences, we calculate the results for the overall sample as well as for the 20% poorest and 20% richest households.

Table 6: Description of scenarios

Scenarios	Description
Implemented	
1	10% subsidy on diesel
2	18% subsidy on electricity
3	10% tax on oil
4	10% subsidy on white appliances
Simulations	
5	10% tax on diesel
6	10% subsidy on ethanol
7	10% tax on oil + 10% subsidy on ethanol
8	10% tax on oil and diesel + 10% subsidy on ethanol
9	10% subsidy on white appliances + 10% tax on electricity

Source: Prepared by the authors.

3.3.2 Welfare Effects

Assuming that prices are fully transferred to consumers, we use the concept of compensated variation (CV) to assess the effects of different energy policies on welfare. The CV, expressed in monetary terms, indicates the adjustment in income a household would need to re-establish its initial utility after a change in prices due to tariff-rate changes. CV can be calculated based on the Hicksian demand function and it can be decomposed into two components: (i) the variation in the tax burden, that is, the variation in the price multiplied by the quantity consumed after the price change and (ii) the excess tax burden, which is the efficiency cost or deadweight loss (DWL). As to the approximation suggested by Harberger (1971)[28]:

$$CV_i \approx -\frac{1}{2}(p_i^1 + p_i^0)(q_i(p_i^1, p_{-i}, y) - q_i(p_i^0, p_{-i}, y)) \tag{22}$$

$$DWL_i \approx (p_i^1 - p_i^0)\frac{(q_i(p_i^1, p_{-i}, y) - h_i(p_i^1, p_{-i}, U_0))}{2} \tag{23}$$

Based on the estimated elasticities, changes in the demand can be calculated

[28] Traditional Harberger-triangle formulas assume that market demand curve comes from utility maximization and that either taxes are small or that demand functions are linear. Therefore, the use of this approximation is good for small policy changes, but can be inaccurate for large ones. Despite of depending on the linearity of the supply and demand curves, the benefit of this method is that it can be used for any type of model if the prices and quantities before and after a policy change are available.

as:

$$\frac{\Delta q_i}{\bar{q}_i} = \sum_{j=1}^{n} \hat{\varepsilon}_{ij}^{M} \tau_j \tag{24}$$

Em que τ_j is the rate of the tax or subsidy applied on the price of good j. The additional tax burden generated by tariff changes can be calculated as:

$$\Delta CT_{ii} = (p_i^1 - p_i^0) \times q_i(p_i^1, p_{-i}, y) = \frac{\tau_i}{1+\tau_i} p_i^1 \times q_i(p_i^1, p_{-i}, y) \tag{25}$$

and total effects of the tax burden were calculated from the following equation:

$$\Delta CT = \sum_{i=1}^{n} \sum_{j=1}^{n} \Delta CT_{ij} \tag{26}$$

It is important to mention that welfare impacts calculated in this study are mainly valid for the short-run. The estimated elasticities should be interpreted as short-term impacts or upper bounds on long-term impacts. In the longer run, averting behavior and substitutions among groups of products certainly affects demand elasticities (Pizer and Sexton, 2017).

3.3.3 Emission Effects

By calculating the total emission coefficient for each good and service i, we created weighted emission coefficient based on the expenditures for each of the 9 groups, as follows:

$$c_{g,CO2eq} = \sum_{i} w_i c_{i,CO_2eq} \tag{27}$$

Therefore, the difference between total GHG emissions before and after the tariff rate changes indicates the changes in total household carbon footprints due to an specific energy tax policy.

4 Results

4.1 CO_2eq emission coefficients

Based on the HIO method, the CO_2eq emission coefficients for each good in the economy are shown in Table 12 (Appendix). The intermediate consumption coefficient represents only the direct emissions, that is, it accounts for the amount of CO_2eq required to produce USD 1 mi of output of each good/service, in 2009 values. The final demand coefficient, in turn, indicates how much CO_2eq is generated considering the emissions throughout the production chain (final demand) - that is, includes both the direct and indirect emissions.

The results indicates that the services under group 4 (Commuting and Transportation), which includes ground transportation of cargo and passengers, as well as air and water transportation are the most carbon intensive services in the Brazilian economy. Goods included in groups 7 (Housing) and 8 (Other goods), which contains products such as wood and paper products, cement, glass, metal and electrical machinery, such as white appliances, also presents a high emission coefficient. Foods and beverages also presents a high CO_2eq emission coefficient, mainly due to the indirect effects from transportation. Since freight and passengers transportation is heavily based on the road mode and use diesel as the main fuel, indirect emissions accounts for the largest part of overall emissions.

The findings are aligned with previous studies conducted specifically for Brazilian households. Using data from 1995–1996, Cohen, Lenzen, and Schaeffer (2005) found that utilities, mobility (transportation) and housing accounted for the majority of energy consumption on that year[29]. An interesting point raised by the authors was that, in general, the energy intensities do not really vary across the income classes, except for mobility - because of the shift from public transport to individual car - and housing - due to differences among rents and appliances between classes. Based on 2003 and 2009 input–output tables from the World Input–Output Database, Perobelli, Faria, and Almeida Vale (2015) found that the largest part of CO_2 emitted by Brazilian households came from transportation services, electricity, gas and water supply, as well as food products. Different from other sectors, the share of CO_2 emissions from transportation services increases with income level.

This pattern is also observed in other empirical studies. Using a 2002 environmentally-extended input–output model, Thomas and Azevedo (2013) shows that gasoline and

[29] The energy intensity was defined as the total primary energy requirement of the product basket of a category divided by the total consumer price of that product and is expressed in MJ/US$ 1996 PPP.

electricity accounts for the largest share of the average U.S. household footprint. With data from 2000, finding from Kerkhof, Nonhebel, and Moll (2009) indicates that Dutch households use gas for home heating and cooking, which highly contributes to CO_2 emissions. Therefore, high emission intensity mainly originates from the use of gas and electricity (grouped as housing), followed by food products due to indirect emissions. Based on an input–output model for carbon emissions, housing is the main source of CO_2 emitted by Chinese households, followed by food, transportation and electricity (Fan et al., 2012; Golley and Meng, 2012). Therefore, based on the total expenditures from the POF, and the estimated CO_2eq emission coefficient, Table 7 presents the total CO_2eq emission by income level. For energy goods, richer households emit almost 14 times more than poorer households; for commuting and transportation services, this proportion is significantly higher (109 times more). For housing and food and catering, richer households tend to emit 7 and 9 times more when compared to poorer households, respectively.

Table 7: Total CO_2eq emissions by income level (per hh/year)

Mean	All sample	20% richer	20% poorer
Food/Catering	3.44	6.29	0.72
Culture/Education	3.20	7.41	0.00
Clothing	0.66	1.65	0.12
Commuting/Transportation	14.72	42.51	0.39
Health/Hygiene	1.31	3.23	0.33
Energy	1.85	5.13	0.36
Housing	1.38	2.81	0.42
Other goods	2.63	4.64	1.46
Other services	0.33	0.39	0.06

Source: Prepared by the authors. 2009 values.

4.2 Demand Estimation

Table 14 (Appendix) presents income, own and cross price elasticities for different household income levels. The expenditure elasticities for domestic energy goods (which mainly includes gas and electricity) are relatively high (1.48), indicating that they are luxury goods for all levels of income - specially for the poorest households (2.11). In contrast, expenditure elasticities for housing (which contains rent, as well as white appliances) are relatively low (0.51) - particularly for high-income groups (0.28). Interestingly, for richer households, commuting and transportation services are considered necessity goods (0.87), while for poorer households they can be classified as superior goods (2.95). Similar results were found for developing countries by Renner, Lay, and Schleicher (2017) (Mexico), by Renner, Lay, and Greve (2018) (Indonesia), and Perobelli, Faria, and Almeida Vale (2015) (Brazil), as well as for developed countries by Schmitz and Madlener (2017) (Germany) and Brännlund, Ghalwash, and Nordström (2007) for Sweden: in general, there is an increasing propensity to consume fuel for mobility was observed as incomes (and therefore expenditures) grow; therefore, public transport expenditure share tends to decline over the expenditure distribution.

All uncompensated own-price elasticities show the expected negative signs and reflect a relatively inelastic household response to energy price changes - specially for the richest households. Commuting and transportation services, as well as housing, presents a lower price elasticity, in particular for poorer households. This indicates that low-income households might be more responsive to a gas tax and less responsive for taxes or subsidies applied on diesel, for example (Levinson and O'Brien, 2015). Significant differences in own-price elasticities are observed according to household income level for food and beverage, housing, clothing and footwear and other goods and services.

Compensated-price elasticities, used in the calculation of welfare effects, differ significantly from uncompensated elasticities since expenditure elasticities are mainly higher than 1. For energy goods, the discrepancy between the compensated and uncompensated elasticities and the high expenditure elasticity suggests that own-price response is primarily driven by income effects. This effect is less evident for commuting and transportation services, as well as housing.

Cross price elasticites (Table 15 - Appendix) indicates that, in general, the groups with high CO_2eq emission coefficient are substitutes for energy goods, that is, food and beverages, housing and commuting and transportation services. Food and beverages, as well as clothing and footwear are also substitutes for housing and commuting and transportation services. Housing is also a substitute for commuting and transportation services. However, energy goods, as well as commuting and transportation services, appears to be complementary for housing.

In general, the findings suggest that the income effects for energy goods outweigh the substitution effects, and changes in their price will have impact on the demand for high CO_2eq intensity goods. Changes on the quantity demanded of other groups (such as housing) appear to have much smaller impact in the consumption of other goods and overall CO_2eq emission.

4.3 Tax Simulations and discussion

The impacts of different energy tax policies are presented in Table 17 (Appendix). As a result of the small share in households expenditures, a subsidy on diesel prices - as recently announced by the Brazilian government - tends to generate a lower tax burden and relatively small economic inefficiencies. On the environmental side, since diesel is the main fuel used for cargo and passangers transportation, subsidies applied on this good increases CO_2eq emissions by 10%.

On the contrary, electricity accounts for a high percentage of household expenditure and, therefore, tends to generate a relatively high compensated variation, tax burden and economic inefficiencies. However, in an aggregate way, a 20% subsidy on electricity prices - as applied in 2013 - decreases CO_2eq emissions by about 30% - as hydropower supplies more than 3/4 of Brazil's electric power. The reduction in the overall emissions comes mainly from richer households, which is explained by the higher cross-price elasticity. Despite of the increase in the consumption of energy goods, there is a reduction in the consumption of commuting and transportation services, which explains the overall reduction of CO_2eq emissions. The effect of a change in electricity price is also potentialized due to the large electricity coverage: in 2009, 98% of the Brazilian households had access to reliable electricity (MME, 2010).

Tax on oil prices appears to affect mainly richer households and, therefore, are relatively more progressive. On the environmental side, a 10% increase in oil prices generates almost 20% increase in total CO_2eq emission. Despite of the decrease in the oil consumption, and consequently, in total consumption of energy goods, there is a increase in the demand for CO_2eq intensive goods - such as food and catering - as well as commuting and transportation services. However, this happens mainly for richer households, as poorer households presents a reduction in total emissions. In this sense, the ability to vary tariff levels according to consumption and income levels could be used to mitigate the impact of electricity price increases on poor households.

Subsidies in white appliances - similar to the one applied in 2013 - appears to benefit more richer households, as shown by the differences in the tax burden. A 10% reduction of white appliances price tends to increase by approximately 7% CO_2eq households emission, as a result of the increase in total emissions from richer households. However, poorer households presents a reduction in total emissions. In particular, these results are aligned with Gertler et al. (2016), Caron and Fally (2018) and Levinson and O'Brien (2015), that shows that households credit constraints become much more likely to purchase energy-using assets with additional income once their income passes a threshold level.

Interestingly, a hypothetical increase in diesel price presents an asymmetric effect when compared to the subsidy: the former has a lower effect on households total expenditure, economic efficiency and emissions. Subsidies on ethanol also generates lower tax burden, deadweight and have a marginal effect on emissions. As several studies point out, price reactions in energy demand might be asymmetric (Gately and Huntington, 2002; Frondel and Vance, 2013). When facing price increases, households are assumed to make efficiency investments that are not reversed when prices decrease again. In this case, the effect of a price increase would be stronger in magnitude compared to that of a price decrease. Furthermore, periods of sustained price increases would generally reduce the responsiveness to price changes.

Tax policies that promotes a more sustainable and renewable energy matrix seems to be progressive and relatively more efficient; however, the impact on total CO_2eq emissions is positive, mainly due to the consumption behaviour of richer households. The results also indicates that combined policies that incentives the purchase of more energy efficient goods - such as a subsidy on white appliances and taxes on electricity - overburden both richer and poorer households and increase the overall CO_2eq emissions. These results suggest that energy tax policies might not be as efficient as they seem in decreasing GHG emissions.

The findings support the international literature on distributional patterns of energy taxes and subsidies, in which indicates that price changes in fuels seems to be less regressive than changes in prices of other energy goods - such as electricity and white appliances. Transport fuel (petrol and diesel) taxes have been shown to be strongly progressive in African and large Asian countries, as well as in Turkey, Chile, Mexico, Costa Rica and Brazil (Pizer and Sexton, 2017; Williams et al., 2014; Lozada and Sterner, 2012; Sterner, 2012; Renner, Lay, and Greve, 2018). However, results for taxes and subsidies applied on electricity varies among countries, mainly due to the electricity coverage (Coady et al., 2015): a large proportion of poor households in developing countries do not benefit from lower electricity tariffs because many do not have access to it and many with larger family sizes (driven by the number of children) consume at levels above “lifeline thresholds.”

5 Conclusions

The recent trend in Brazilian GHG emissions indicates that a larger share of the overall emissions are being generated by the energy sector. At the same time, taxes and subsidies are economic instruments used as a lever for different policy purposes. Understanding who benefits from energy price taxes and subsidies and their welfare impacts policies are key to gaining public support for a greener energy matrix.

In this paper, we have estimated short-run emissions and distributional effects of energy price changes in a partial equilibrium framework. As recently implemented by the Brazilian government, taxes and subsidies in fuel prices (oil and diesel, respectively) are progressive, but have positive impact on total household emissions due to substitution effects. Despite being regressive, changes in electricity price have large effects on household emissions due to the particularities of the Brazilian electric supply and coverage.

By simulating hypothetical price change scenarios in policies considered more environment-friendly, the evidence shows that are tradeoffs between welfare and emissions. Alternative policies that subsidizes ethanol have a small but positive effect on the economy and tends to reduce households emissions. However, large substitution effects when also taxing oil do not offset the reduction in emissions caused by a lower ethanol price. Policies that promotes a more efficient use of electricity are regressive and increase households carbon footprints. Therefore, the distributional effects on welfare is a crucial factor to be taken into account when designing policies that advocates for emission reduction.

Aligned with the international empirical evidence, this study confirm that a very large share of benefits from energy price subsidies might be appropriated by high-income households, further reinforcing existing income inequalities. It should be emphasized that the regressivity and progressivity of energy taxes is likely to change over time. In this sense, further analysis is required to understand the long-term consumption patterns and the potential emission effects associated with energy tax policies. More in-depth studies should also analyze to what extent the effects of non-price instruments (such as feed-in-tariffs or energy efficiency standards) would differ from the findings presented in this study.

In addition, since Brazilian high-income households are responsible for the largest share of changes in total emissions, it is likely that a "carbon tax" would affect richest households far more than the poorest households. This conclusion is backed up by several reports, which indicates that carbon taxation and fuel excises on gasoline have had a progressive effect in Mexico, with 52% of the tax being paid by the richest income quintile (Aiello et al., 2018). Therefore, empirical evidence of the effects of a "carbon tax" and its welfare impacts are still needed for Brazil.

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6 Appendix

Table 14: Expenditure and price elasticities estimated using Censored QUAIDS model (beta/se): full sample, 20% poorest, and 20% richest.

Groups	Full Sample			20% richest			20% poorest		
	η_i	ϵ_{ii}	ϵ_{ii}^H	η_i	ϵ_{ii}	ϵ_{ii}^H	η_i	ϵ_{ii}	ϵ_{ii}^H
Food/catering	0.6011***	-0.5657 ***	-0.4857 ***	0.4035***	-2.20665 *	-2.15006 ***	0.3109***	-0.508 ***	-0.291 ***
		(0.020)	(0.011)		(0.084)	(0.055)		(0.035)	(0.084)
Recreation/education	1.1168***	-0.571 ***	-0.5108 ***	0.6683***	-0.75316 **	-0.62541 ***	3.0928***	-0.491 ***	-0.47 ***
		(0.036)	(0.012)		(0.038)	(0.035)		(0.021)	(0.084)
Clothing/footwear	1.0807***	-0.5596 ***	-0.3797 ***	1.1329***	-1.01523 **	-0.72112 ***	1.1656***	-0.508 ***	-0.3673 ***
		(0.013)	(0.006)		(0.024)	(0.010)		(0.099)	(0.084)
Commuting/Transportation	1.2712***	-0.2745 ***	-0.1872 ***	0.8706***	-0.61101 **	0.52179 ***	2.9530***	-0.202 ***	-0.1716 ***
		(0.020)	(0.012)		(0.0190)	(0.018)		(0.053)	(0.084)
Health and Hygiene	1.8733***	-2.3416 ***	-2.2478 ***	1.6892***	-2.09055	-2.05534 ***	1.6961***	-2.394 ***	-2.2961 ***
		(0.052)	(0.023)		(0.1376)	(0.134)		(0.019)	(0.084)
Energy	1.4801***	-0.908 ***	-0.6279 ***	1.7251***	-0.84827 *	-0.56185 ***	2.1160***	-0.923 ***	-0.6999 ***
		(0.018)	(0.010)		(0.0277)	(0.019)		(0.064)	(0.084)
Housing	0.5121***	-0.0331	0.0019 ***	0.2849***	-0.90303 **	-0.73256 ***	0.5871***	-0.192 ***	-0.141 ***
		(0.018)	(0.011)		(0.0332)	(0.026)		(0.005)	(0.084)
Other goods	0.3160***	-1.1347 ***	-0.9976 ***	0.4400***	-0.66302 *	-0.60763 *	0.1844***	-1.169 ***	-0.9734 ***
		(0.027)	(0.015)		(0.0670)	(0.040)		(0.004)	(0.084)
Other services	1.0538***	-0.0941 *	-0.055	0.8697***	-0.67918 **	-0.59366 **	3.8085***	-0.035	-0.0233
		(0.041)	(0.058)		(0.0480)	(0.073)		(0.419)	(0.084)

Note: $*$ p-value<0.10, $**$ p-value $<$ 0.05, $***$ p-value<0.01. η_i represents the expenditure elasticity, ϵ_{ij} and ϵ_{ij}^H represents the Marshallian and Hicksian price elasticities, respectively.

Table 8: CO_2eq emission coefficients (tCO2eq / USD mi) from intermediate consumption and final demand for each good/service in the economy (2010)

Group	Good/service (IO)	Int. Consump.	Final Demand
4	Cargo transportation	3,778	8,044
4	Passengers transportation	3,672	7,821
4	Air transport	2,011	3,821
4	Water transportation	1,760	3,813
8	Wood products, exclusive furniture	1,097	3,072
8	Paper, paperboard and paper articles	1,093	3,066
7	Printing and services	1,020	2,880
8	Cement, plaster	646	2,067
8	Glass, ceramics and others	618	2,001
8	Metal products, excl. Machines and equipment	397	1,897
1	Pork	46	1,254
1	Processed fish	45	1,253
2	Smoking products	47	1,253
7	Animal feed	46	1,251
1	Other Dairy Products	54	1,249
1	Coffee (processed)	48	1,247
1	Meat of bovine animals and other prod. Of meat	46	1,247
1	Drinks	46	1,247
1	Canned fruits, vegetables and fruit juices	46	1,246
8	Non-Metallic Minerals	346	1,230
6	Mineral coal	334	1,201
1	Sugar	58	1,200
1	Products derived from wheat, manioc or maize	69	1,199
5	Perfumery, soaps and cleaning products	176	1,196
1	Sterilized and pasteurized milk	42	1,190
1	Processed rice and products	65	1,188
7	Advertising and other technical services	419	1,184
1	Poultry meat	41	1,176
1	Oils and fats, vegetable and animal	43	1,176
5	Other products	158	1,164
8	Inorganic chemicals	161	1,149
8	Paints, varnishes, enamels and lacquers	154	1,142
8	Plastic articles	149	1,132
8	Detergents and household cleaning products	140	1,118

Source: Based on data from National Account System (2010) and the Brazilian Energy Matrix (2010). Prepared by the author. USD in 2009 values.

Table 10: CO_2eq emission coefficients (tCO2eq / USD mi) from intermediate consumption and final demand for each good/service in the economy (2010) (cont.)

Group	Good/service (IO)	Int. Consump.	Final Demand
8	Rubber articles	138	1,109
8	Detergents and household cleaning products	140	1,118
8	Rubber articles	138	1,109
1	Other Food Products	41	1,107
8	Forestry	353	1,080
5	Pharmaceutical products	131	1,063
1	Sugarcane	343	1,058
1	Fisheries	343	1,058
1	Soybeans	343	1,058
1	Poultry and eggs	343	1,058
1	Orange	343	1,058
1	Swine	343	1,058
1	Milk (cows and other animals)	342	1,058
1	Bovine animals	342	1,058
1	Other (permanent) agriculture	342	1,056
1	Other (temporary)	341	1,054
1	Corn	340	1,050
1	Rice	335	1,038
6	Ethanol and other biofuels	103	1,009
8	Goods of other enterprises	61	867
9	Other machines and mechanical equipment	53	858
6	Electricity, gas and other utilities	140	824
6	Gasoalcool	141	823
6	Diesel - biodiesel	141	823
8	Other Petroleum Refining Products	136	808
4	Aircraft, boats and other transport equipment	33	806
7	Electrical machinery and equipment	31	803
4	Trucks and buses	30	799
9	Equip. for measurement, testing	31	799
7	Home appliances	32	798
7	Furniture	32	795
7	Electronic material and Communications equip.	28	795
4	Automobiles, trucks and commercial vehicles	27	793
9	Office machines and equipment.	29	790

Source: Based on data from National Account System (2010) and the Brazilian Energy Matrix (2010). Prepared by the author. USD in 2009 values.

Table 12: CO_2eq emission coefficients (tCO2eq / USD mi) from intermediate consumption and final demand for each good/service in the economy (2010) (cont.)

Group	Good/service (IO)	Int. Consump.	Final Demand
3	Yarn and textile fibers	62	692
3	Art. Textiles for household and others	41	679
3	Textiles & Leather Products	37	666
3	Footwear and leather goods	36	661
3	Clothing articles and accessories	34	651
7	Rent and real estate services	89	588
4	Warehousing and others	95	531
7	Wholesale trade and sale, except motor vehicles	9	376
7	Maintenance of computers, telephones	5	363
9	Other administrative services	9	361
7	Manag. of Intellectual Property Assets	6	360
4	Trade and repair of vehicles	5	359
2	Accommodation services in hotels and similar	7	354
7	Courier and other delivery services	5	353
7	Employers' organizations, trade union	5	353
7	Condos and building services	5	353
7	Surveillance, security and investigation services	5	353
7	Domestic services	5	353
7	Personal Services	5	353
7	Telecommunications and others	5	353
2	Film, music, radio	5	353
7	Financial services, insurance	5	353
2	Food services	5	353
9	Systems dev. and IT services	5	352
2	Books, newspapers and magazines	5	352
2	Arts, culture and recreation services	5	350
7	Architectural and engineering services	5	350
5	Private health	5	349
7	Legal services, accounting	5	348
2	Private education	5	347
9	Public administration	12	192
7	Water, sewage	12	192

Source: Based on data from National Account System (2010) and the Brazilian Energy Matrix (2010). Prepared by the author. USD in 2009 values.

Table 15: Marshallian (ϵ_{ij}) price elasticities using Censored QUAIDS, full sample

	1		2		3		4		5		6		7		8		9	
1 Food/catering	-0.5657	***	-0.24741	***	0.21043	***	-0.12492	***	-1.13053	***	-0.30091	***	0.71288	***	-0.71019	***	-0.34054	***
2 Recreation/education	0.27869	***	-0.57097	***	0.17822	***	-0.02548	***	-1.34158	***	-0.26624		0.57713	***	-0.76439	***	-0.04157	***
3 Clothing/footwear	0.36872	***	-0.30866	***	-0.55964	***	-0.33972	***	-1.41454	***	-0.39791	***	0.6174	***	-0.43301	***	-0.50854	***
4 Commuting/Transportation	0.26518	***	-0.14735		0.11006	***	-0.27449	***	-1.41378		-0.28316		0.54403	***	-0.81424	***	-0.21427	***
5 Health and Hygiene	0.38491	***	0.42903	***	0.1931	***	0.02238	***	-2.34158	***	-0.28898	***	0.48057	***	-0.76439	***	-0.03659	***
6 Energy	0.30219	***	-0.04107	***	0.15632	***	0.0141	***	-1.56695	***	-0.90801	***	0.33881	***	-0.92497	***	-0.00193	***
7 Housing	0.39972	***	-0.23001	***	0.15551	***	-0.15577	***	-1.62395	***	-0.45091	***	-0.03309		-0.35735	***	-0.07104	***
8 Other goods	0.24646	***	-0.17848	***	0.16801	***	-0.08959	***	-1.26576	***	-0.32627	***	0.59079	***	-1.13468	***	-0.20569	***
9 Other services	0.26845	***	-0.09164		0.13056	***	-0.069	***	-1.35393		-0.27181		0.61183	*	-0.66947	***	-0.09411	*

Note: $*$ p-value<0.10, $**$ p-value $<$ 0.05, $***$ p-value<0.01. Diagonals represent the own-price elasticities.

Table 16: Hicksian (ϵ_{ij}^{H}) price elasticities using Censored QUAIDS, full sample

	1		2		3		4		5		6		7		8		9	
1 Food/catering	-0.48568	***	-0.06828	***	0.32706	***	0.03559	***	-0.66177	***	-0.08851	***	0.75909	***	-0.45235	*	-0.17278	
2 Recreation/education	0.30558	***	-0.51084	***	0.21737	***	0.0284	***	-1.18423		-0.19494	*	0.59264	***	-0.67784	***	0.01474	
3 Clothing/footwear	0.49232	***	-0.03226		-0.37967	***	-0.09204	**	-0.69121		-0.07018		0.68872	***	-0.03515	***	-0.24968	
4 Commuting/Transportation	0.30876	***	-0.04989	***	0.17352	***	-0.18716	***	-1.15875		-0.16761		0.56917	**	-0.67396	***	-0.123	***
5 Health and Hygiene	0.40094	***	0.46488	***	0.21644	***	0.0545	*	-2.24777	***	-0.24648	***	0.48982		-0.71279	***	-0.00302	
6 Energy	0.40784	***	0.19517	***	0.31015	***	0.22579	***	-0.94871	*	-0.6279	***	0.39976		-0.58492	***	0.21932	
7 Housing	0.46038	***	-0.09437		0.24382	***	-0.03423	***	-1.269		-0.29009	**	0.0019	***	-0.16211	***	0.05599	
8 Other goods	0.28906	***	-0.08323	***	0.23003	***	-0.00423		-1.01648	***	-0.21333	***	0.61537	***	-0.99757	***	-0.11648	
9 Other services	0.28712		-0.0499		0.15774		-0.0316	***	-1.24467		-0.22231		0.62261		-0.60938		-0.05501	

Note: $*$ p-value<0.10, $**$ p-value $<$ 0.05, $***$ p-value<0.01. Diagonals represent the own-price elasticities.

Table 17: Simulation results for full sample, 20% poorest, and 20% richest.

	Scenarios	Full sample					20% richest				20% poorest			
		CV/hh	Tax Burden/hh	DWL/hh	Emissions (tCO2eq/hh)	Total Emissions - BR	CV/hh	Tax Burden	DWL/hh	Emissions (tCO2eq/hh)	CV/hh	Tax Burden/hh	DWL/hh	Emissions (tCO2eq/hh)
Implemented	10% subsidy on diesel	-1.78	-0.03%	-0.06147	0.01	9.36%	-4.78	-0.06%	-0.061	0.08	-0.10	0.00%	-0.005	0.00
	18% subsidy on electricity	-65.18	1.33%	-4.17977	-0.32	-29.61%	-94.18	0.78%	-4.180	-1.68	-10.01	0.68%	-2.143	0.11
	10% tax on oil	40.44	0.35%	-1.547	0.19	17.39%	106.14	0.77%	-1.547	1.86	2.09	0.02%	-0.100	-0.02
	10% subsidy on white appliances	-8.90	-0.02%	-0.43387	0.08	7.09%	-11.38	-0.19%	-0.434	1.55	-5.57	-0.27%	-0.113	-0.05
Simulations	10% tax on diesel	2.12	0.00%	-0.00405	0.01	0.90%	4.40	0.00%	-0.004	0.08	0.21	0.00%	0.001	0.00
	10% subsidy on ethanol	-4.24	-0.01%	-0.01915	-0.02	-1.96%	-12.80	-0.01%	-0.019	-0.23	-0.30	0.00%	-0.002	0.00
	10% tax on oil + 10% subsidy on ethanol	35.78	0.21%	-1.36952	0.18	16.51%	92.81	0.47%	-1.370	1.82	1.82	0.01%	-0.087	-0.05
	10% tax on oil and diesel + 10% subsidy on ethanol	37.68	0.27%	-1.4416	0.18	16.87%	97.25	0.56%	-1.442	1.83	2.07	0.02%	-0.099	-0.02
	10% subsidy on white appliances + 10% tax on electricity	-38.96	-1.74%	-1.73193	0.07	6.18%	-55.46	-0.81%	-1.732	1.49	-9.65	-0.79%	-0.327	-0.04

Note: CV indicates compensated variation and DWL, deadweight loss. CV, Tax Burden and DWL in USD/year (2009 values) and total emissions in tCO2eq/hh.

6.1 Price correction for food and beverages

To account for differences in quality and packaging, Cox and Wohlgenant (1986) consider that quality effects are expressed as deviations of unit values from regional or seasonal means. Thus, they regress the mean-deviated unit values on household characteristics to exclude the quality effects from unit values. In order to adjust this method to the assumption of common market prices[30], as well as to overcome the error measurement issue, we follow Lazaridis (2003) and Brooks and Lusk (2010) and extend the controls used by Cox and Wohlgenant (1986):

$$UV_i - U\bar{V}_n = \sum_{l}^{L} \beta_{il} Z_l + \sum_{c}^{C} \omega_{ic} D_{ic} + \sum_{m}^{M} \theta_{im} V_{im} + \sum_{s}^{S} \sum_{m}^{M} \delta_{ism} U_{is} V_{im} + \epsilon_i \tag{28}$$

in which UV_i is the unit value (total expenditure divided by consumed quantity) of good i, $U\bar{V}_n$ represents its corresponding cluster mean, Z is a vector of household characteristics, D_{ic} is a dummy for cluster and V_{im} represents a dummy variable for group m and L, C and M are the sets of household characteristics, cluster and group indexes, respectively.

The quality-adjusted prices for each item of the group Food and Catering, p_i, is generated by adding the mean unit value to the residual derived from Equation (28):

$$p_i = U\bar{V}_n + \hat{\epsilon}_i \tag{29}$$

[30] See footnote 27.