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Essays on Energy and Natural Gas Industry

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Essays on Energy and Natural Gas Industry

Tese para obtenção do grau de Doutor em Economia apresentada à Escola de Pós Graduação em Economia.

Orientador: Cézar Augusto Ramos Santos

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Resumo

Esta tese consiste em três artigos independentes focados em economia da energia. O primeiro artigo investiga como o aumento da concorrência no setor de producão de gas natural impactaria as distribuidoras de gas natural e as economias regionais ao longo do tempo. O segundo artigo avalia o aumento de e ciência que uma distribuidora de gas natural deve atingir apos a privatizacão para fazer com que essa privatizacão valha a pena para o Estado, do ponto de vista scal. O terceiro artigo estuda como os precos e as mudancas tecnologicas impactam o consumo residencial de energia eletrica por fam lias heterogêneas com diferentes n veis de renda.

KEYWORDS: Economia da Energia, Industria de Gas Natural, Agentes Heterogêneos

Abstract

This thesis consists of three independent papers focused on energy economics. The first paper investigates how increasing competition in the natural gas production sector would impact natural gas local distribution companies and regional economies over time. The second paper evaluates the increase in efficiency should a natural gas local distribution company attain after being privatized in order to make this privatization worth in a state-level fiscal sense. The third paper studies how prices and technological changes impact residential electric energy consumption by heterogeneous households with different income levels.

KEYWORDS: Energy Economics, Natural Gas Industry, Heterogeneous Agents

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Chapter 1

When is it Worth Privatizing Local Distribution Companies? Reforms in the Brazilian Natural Gas Sector

Abstract

This paper evaluates the increase in efficiency should a natural gas local distribution company (LDC) attain after being privatized in order to make this privatization worth in a state-level fiscal sense. I propose a structural economic model representing the economy of a region supplied by a monopolistic LDC, whose ownership is shared between the private sector and both federal and state governments. The model is calibrated for 13 of the major brazilian LDCs using their financial and operational data, as well as regional economic data. I found out that the necessary cost efficiency gain needed varies between LDCs, with an average of 6.6% and values ranging from 0.2% to 22.9%.

1.1 Introduction

Natural gas is an important energy input used by different sectors of the economy. They represent 13.1% of total Brazilian consumption in terms of energy, acording to EPE (2020). In particular, its consumption is especially relevant in the electrical and industrial sectors, although it is also increasingly consumed in residences, commercial establishments and as automotive fuel in compressed form (CNG).

There is currently a debate in Brazil on ways to make natural gas cheaper and more accessible. I can highlight the recently sanctioned Law No. 14134/2021, known as the New Gas Law. The main aspects of this law include the privatization of local distribution companies (LDC, henceforth), as well as increased competition in gas production. There is an expectation within agents that this reform will lead to a reduction in the tariff paid by consumers.

In this article I propose a structural economic model representing the economy of a certain region supplied by a monopolistic natural gas LDC, whose ownership is shared between the private sector and both federal and state governments. The model is characterized by a representative agent that demands a final consumption good, supplying labor in an elastic way, and a productive sector broken down into sub-sectors that demand labor and natural gas as production inputs. The LDC is a monopolist that sells natural gas to different sectors at different rates, and a producer supplies gas inelastically to the LDC at a constant and exogenous price. Wages and prices for intermediate goods are determined through a general equilibrium setting.

I calibrated the model for 13 major Brazilian LDCs, using financial and operational data from these distributors, as well as economic data from the regions they supply, as target statistics for calibration. With the calibrated model, I calculate the distribution efficiency gain necessary for the privatization of LDCs to be advantageous from the states' fiscal point of view. In other words, this is the same as finding the point where the increase in state tax revenue equals the loss of dividends. I also study the economic effects of increased competition in gas production, synthesized here as a reduction in the price of natural gas purchased by LDCs.

A certain heterogeneity in the need for distribution efficiency gains among LDCs to make privatization advantageous from a fiscal point of view was observed. This efficiency gain, measured as a reduction in the unit distribution cost, had a median value of 4.4%, with values ranging from 0.2% to 22.9%. Meanwhile, when reducing natural gas price, I observed that a drop of only 5% had some impact on long run GDP for some regions, averaging 0.72% and reaching up to a 2.5% increase.

There is evidence in the economic literature that energy consumption per capita is positively related to economic growth (Soytas and Sari (2009), Fei et al. (2011), Mahadevan and Asafu-Adjaye (2007)). This connection is also true for the particular case of natural gas consumption (Sasana (2017), Cheng (1997), Poveda and Martínez (2011), Zhixin and Xin (2011)). Most economic growth models do not highlight energy as an important input like labor and capital. However, some examples like Alpanda and Peralta-Alva (2010) and Stern (2015) do use energy as inputs for the production function. In this work, I use energy coming from natural gas as a relevant production input.

The Brazilian natural gas sector is still mostly controlled by Petrobras, who not only hold monopoly over production but also has a stake in most LDCs (Mathias and Szklo (2007)). The feature of monopolistic LDCs is highlighted in this work, with tariffs being set not in a competitive framework, but as a decision from the distribution companies given the demand curves they face.

There is an ongoing discussion about relevant reforms for the sector. Leal, Rego, and Oliveira Ribeiro (2019) propose changes in the Brazilian regulatory framework in order to ensure better long term incentives to production and distribution companies to invest, also in line with a transition towards lower emission energy system. In the U.S., deregulation of fuel-fired power plants led to a decrease in the price paid for coal, but not for natural gas (Cicala (2015)). Rossi (2001) estimates a 4% gain in efficiency after 10 year due to the privatization of Argentinian LDCs, which is in line with the values that I found for Brazil in order to make privatization fiscally advantageous.

1.1.1 The natural gas industry in Brazil

The path that natural gas takes from the natural deposit to the final consumer can be divided into three segments: production, transportation and distribution. Production consists in finding, extracting and processing the natural gas coming from underground reservoirs. Transportation is usually done through high-pressured pipelines, over longer distances. Finally, distribution is performed in smaller distances but to a more diverse range of final consumers.

Even though the Federal Constitution of 1988 establishes that the States are responsible for the activities of distribution, up until 1995 the state-owned Brazilian oil company Petrobras held monopoly over all activities related to the natural gas industry, such as production and distribution. Since then, some reforms have aimed to increase competition in the sector, but not necessarily fulfilling this goal.[1]

The Law 9.478 (Oil Law) from 1997 aimed to break Petrobras' monopoly over the activities of research, exploration, production and refine of oil and natural gas. In the end, even as other companies were allowed to participate in these activities, they were obliged to work along with Petrobras, who held a stake on every activity. The Law 11.909 (Natural Gas Law) from 2009 aimed more directly to the natural gas sector, abolishing the state monopoly. Even with the privatization of some companies, Petrobras still hold a stake on most of the LDCs. The exceptions are the LDCs from Rio de Janeiro and São Paulo, which were privatized in 1998 and 1999, respectively.

1.2 Model

There is an economy with both natural gas production and distribution sectors, J productive sectors, a final consumption good sector, residential sector and government. Each of them is described below. Finally, I define the equilibrium in this economy.

1.2.1 Natural gas production

Natural gas production is carried out by a firm that supplies natural gas to the LDC in an infinitely elastic way, that is, at a fixed price p, regardless of the quantity sold.[2] The marginal cost for the producer firm is constant and equal to z_p. This cost is in numeraire good units, that is, for each unit of gas produced, z_p units of final consumption good are spent. The firm's net profit is given by $(p - z_p)\, g$, where g is the amount of gas sold to the LDC. The total production cost is given by $K_p = z_p g$.

1.2.2 Natural gas distribution

The natural gas distribution is done by a monopolistic LDC that buys a quantity g of natural gas from the producer, for a fixed price p, and distributes it to other sectors of the economy, charging different tariffs t_i for each sector i. A tax upon the LDC's added

[1] A good outline of the Brazilian natural gas industry, from a historical point of view, can be found in Junior and Almeida (2007).

[2] The assumption of exogenous price is justified by the fact that natural gas prices are driven by oil prices, which are in turn determined globally, and hardly affected by a local economy alone.

value is levied by the state government, with tax rate given by τ. Since I is the number of sectors to which the distributor sells natural gas, its net profit is given by

$$\Pi_d = \max_{(t_i)_{i=1}^{I}} \sum_{i=1}^{I} \left[(1-\tau)(t_i - p) - z_i\right] g_i(t_i)$$

where z_i is the distribution cost (in units of final consumption good) per unit of natural gas for sector i, and $g_i(t_i)$ is the sectorial demand curve. The first order conditions of the maximization problem tell us that the optimal tariffs satisfy

$$t_i = \mu_i(t_i)\left(p + \frac{z_i}{1-\tau}\right) \tag{1.1}$$

$$\mu_i(t_i) = \frac{\varepsilon_i(t_i)}{\varepsilon_i(t_i) - 1} \tag{1.2}$$

$$\varepsilon_i(t_i) = -t_i \frac{g_i'(t_i)}{g_i(t_i)} \tag{1.3}$$

with $\mu_i(t_i)$ being the mark-up and $\varepsilon_i(t_i)$ the price elasticity of natural gas demand for sector i. Therefore, net profit is given by $\Pi_d = \sum_{i=1}^{I}\left[\mu_i(t_i) - 1\right]\left[(1-\tau)p + z_i\right] g_i(t_i)$ and total cost, net of natural gas purchase expenses, is $K_d = \sum_{i=1}^{I} z_i g_i(t_i)$.

1.2.3 Intermediate sectors

In the production side of the economy there are J intermediate sectors, each represented by a representative competitive firm. Firm j produces a quantity y_j of the intermediate good j, using natural gas (g_j) and labor (l_j) as inputs, with respective prices t_j and w, selling this intermediate good to the final consumption good producer for a price p_j. A τ value-added tax is levied by the state government. Note that, in this model, the added value of the sector j is given by the expenditure on labor. The production technology is a constant elasticity of substitution (CES) function given by

$$y_j = F_j(g_j, l_j) = \left[\alpha_j g_j^{\frac{\rho_j - 1}{\rho_j}} + (1-\alpha_j)\, l_j^{\frac{\rho_j - 1}{\rho_j}}\right]^{\frac{\rho_j}{\rho_j - 1}} \tag{1.4}$$

Therefore, the firm's profit optimization requires that

$$t_j = p_j \alpha_j \left(\frac{y_j}{g_j} \right)^{\frac{1}{\rho_j}}, \quad j = 1, \ldots, J \tag{1.5}$$

$$w = (1 - \tau)\, p_j \,(1 - \alpha_j) \left(\frac{y_j}{l_j} \right)^{\frac{1}{\rho_j}}, \quad j = 1, \ldots, J \tag{1.6}$$

We have that the price elasticity of natural gas demand for sector j is constant and equal to ρ_j.[3]

1.2.4 Final consumption good sector

A single final consumption good is produced by a representative competitive firm using intermediate goods and residential natural gas as inputs. Its production technology is given by

$$y = F_0\left(g_0, (c_j)_{j=1}^J\right) = A \left[\left(1 - \sum_{j=1}^J \beta_j\right) g_0^{\frac{\rho_0 - 1}{\rho_0}} + \sum_{j=1}^J \beta_j c_j^{\frac{\rho_0 - 1}{\rho_0}} \right]^{\frac{\rho_0}{\rho_0 - 1}} \tag{1.7}$$

where y is the quantity of final good produced, g_0 is the residential natural gas demand and c_j is the intermediate good j demand. The price of the final consumption good is normalized to 1. First order conditions are

$$t_0 = A^{\frac{\rho_0 - 1}{\rho_0}} \left(1 - \sum_{j=1}^J \beta_j\right) \left(\frac{y}{g_0} \right)^{\frac{1}{\rho_0}} \tag{1.8}$$

$$p_j = A^{\frac{\rho_0 - 1}{\rho_0}} \beta_j \left(\frac{y}{c_j} \right)^{\frac{1}{\rho_0}} \quad j = 1, \ldots, J \tag{1.9}$$

The price elasticity of residential natural gas demand is also constant and equal to ρ_0.

1.2.5 Residential sector

Residential consumers are represented by a single agent that consumes a quantity c of the final good, supplying a quantity of labor 1. Preferences are described by a GHH utility function.[4] For each unit of final consumption good, the consumer pays a normalized

[3] By implicitly differentiating Equation 1.5 with respect to t_j, under the assumption that p_j and y_j are given, and also using the elasticity definition from Equation 1.3, we conclude that $\varepsilon_j(t_j) = \rho_j$.

[4] The Greenwood-Hercowitz-Huffman (GHH) functional form for preferences is mathematically convenient to work with, as closed-form expressions for consumption good demand and labor supply are easily obtained.

unit price and for each unit of work supplied the consumer receives w. In addition, the consumer also receives a lump sum transfer T from the government, as well as part of the net profits from the natural gas producer and the LDC, Π_p and Π_d. Here, π_p^f, π_d^f and π_d^e are, respectively, the federal government's participation in the production sector and in the LDC, and the state government's participation in the LDC. The consumer optimization problem is described by:

$$\max_{c,l} c - \psi \frac{l^{1+\theta}}{1+\theta} \tag{1.10}$$

subjet to the budget constraint

$$c = wl + T + \left(1 - \pi_p^f\right) \Pi_p + \left(1 - \pi_d^e - \pi_d^f\right) \Pi_d \tag{1.11}$$

The analytical solution to the consumer optimization problem gives us the following expressions for optimal choices:

$$l = \left(\frac{w}{\psi}\right)^{\frac{1}{\theta}} \tag{1.12}$$

$$c = w\left(\frac{w}{\psi}\right)^{\frac{1}{\theta}} + T + \left(1 - \pi_p^f\right) \Pi_p + \left(1 - \pi_d^e - \pi_d^f\right) \Pi_d \tag{1.13}$$

1.2.6 Government

This economy has two spheres of government: federal and state. The federal government receives a share π_p^f of the natural gas producer's net income and a portion π_d^f of the LDC's net profit, financing consumption c^f of final goods by the federal government. In the case of state government, its revenue comes from taxes on the LDC's and intermediary sectors' added value (τ_e), as well as a portion of π_d^e of the LDC's profit. This state revenue, unlike the federal one, returns to the economy through T transfers to the residential sector. Therefore, the total state government revenue in this economy is given by:

$$R_e = \underbrace{\pi_d^e \Pi_d}_{\text{LDC's profit}} + \underbrace{\tau \sum_{i=0}^{I} (t_i - p)\, g_i}_{\text{LDC's taxes}} + \underbrace{\tau \sum_{j=1}^{J} (p_j y_j - t_j g_j)}_{\text{Intermediate sectors' taxes}} \tag{1.14}$$

The federal government's revenue is given by:

$$R_f = \underbrace{\pi_p^f \Pi_p}_{\text{NG production firm's profit}} + \underbrace{\pi_d^f \Pi_d}_{\text{LDC's profit}} \tag{1.15}$$

1.2.7 Equilibrium

Given natural gas price p, the equilibrium is characterized by prices $\left((t_i)_{i=1}^{I}, (p_j)_{j=1}^{J}, w \right)$, allocations $\left(c, l, y, g, (c_j)_{j=1}^{J}, (y_j)_{j=1}^{J}, (g_i)_{i=1}^{I}, (l_j)_{j=1}^{J} \right)$, transfers T, net profits Π_p and Π_d, total costs K_p and K_d, and federal government consumption c^f such that:

1. Given (w, T, Π_p, Π_d), (c, l) maximize the utility of the representative consumer, satisfying (1.11), (1.12) and (1.13);
2. Given $\left(t_0, (p_j)_{j=1}^{J} \right)$, $\left(y, g_0, (c_j)_{j=1}^{J} \right)$ maximize the final consumption good firm profit, satisfying (1.7), (1.8) and (1.9).
3. Given $\left((p_j)_{j=1}^{J}, (t_j)_{j=1}^{J}, w \right)$, $(y_j, g_j, l_j)_{j=1}^{J}$ maximize the intermediate goods firms profits, satisfying (1.4), (1.5) and (1.6);
4. Tariffs $(t_i)_{i=0}^{I}$ satisfy the optimality conditions for the monopolistic LDC described by (1.1);
5. Final consumption good market clears: $K_p + K_d + c_f + c = y$;
6. Intermediate goods markets clear: $c_j = y_j, \quad j = 1, \ldots, J$
7. Natural gas market clears: $\sum_{i=1}^{I} g_i = g$;
8. Labor market clears: $\sum_{j=1}^{J} l_j = l$;
9. Balanced federal government budget: $R_f = c^f$;
10. Balanced state government budget: $R_e = T$;
11. Natural gas producer profit: $\Pi_p = (p \quad z_p)\, g$;
12. LDC profit: $\Pi_d = \sum_{i=1}^{I} [\mu_i (t_i) \quad 1] [(1 \quad \tau) p + z_i] g_i$;
13. Total natural gas production cost: $K_p = z_p g$;
14. Total natural gas distribution cost: $K_d = \sum_{i=1}^{I} z_i g_i$.

1.3 Setting the Model Parameters

In order to discipline the model so that it presents a behavior closer to reality, we need to properly adjust the parameters. To do so, I took a set of real statistics that have a counterpart in the model and chose the parameters so that the model moments are close to data moments.

I selected 13 LDCs from ten different Brazilian states to carry out the numerical experiments, so that each one of them has a different adjustment for the parameters, according to their particularities. I selected those companies with greater volumes of natural gas sold, but also according to availability of data.

Of the sectors to which LDCs sell natural gas, I highlighted the electrical, industrial, commercial and residential sectors. Within the model, I consider sales to the residential sector as sales to the final consumption good sector, as this sector is just an abstraction for having a single final consumption good. Furthermore, all sectors that purchase gas other than any of the four described above are aggregated into a single sector called "others". Therefore, I worked with $J = 4$ intermediate sectors in the model (electrical, industrial, commercial and others).

1.3.1 Adjustment of natural gas production and distribution parameters

To set the parameters of the model's production and distribution sector, I used financial information, natural gas volumes, tariffs, among others, obtained for the different LDCs. Such data, for the most part, are average values observed in the period between 2014 and 2019. It was important to consider a longer range of years for the values, since taking only the nearest period of 2019 would subject data to punctual fluctuations in revenue and costs due to non-recurrent events. Taking the average of the last 6 years was a way to smooth this, and get a better picture of the LDCs' overall situation.

Some of the information were directly available in the financial and operational reports of the LDCs, as well as in some tables made available by the Brazilian Association of Piped Natural Gas Distribution Companies (Abegás). Other information, however, were not directly available and had to be estimated. The Table 1.1 presents the calculated values for the parameters of production and distribution costs. Below I detail the choice for each parameter.[5,6]

LDC	Natural gas sector cost parameters (R$/m³)						
	p	z_p	residential z_0	electrical z_1	industrial z_2	commercial z_3	others z_4
Sulgas	0.84	0.74	1.91	-	0.22	1.12	0.14
SCGas	0.89	0.79	1.21	-	0.40	0.78	0.37
Compagas	1.05	0.93	0.60	0.42	0.41	0.51	0.39
Comgas	0.73	0.64	2.69	0.40	0.54	1.49	0.41
Gas Brasiliano	1.00	0.88	1.74	-	0.48	0.90	0.42
Naturgy Sao Paulo	0.99	0.88	1.52	-	0.49	1.15	0.37
Naturgy Rio Capital	0.81	0.71	3.37	-0.13	0.59	1.51	0.82
Naturgy Rio Interior	0.77	0.68	0.99	0.13	0.16	0.65	0.15
Gasmig	1.17	1.04	1.02	0.37	0.33	0.69	0.48
ESGas	0.99	0.88	1.66	0.22	0.22	0.59	0.20
MSGas	0.45	0.40	0.43	0.06	0.19	0.36	0.12
Bahiagas	1.01	0.89	0.78	0.25	0.30	0.38	0.30
Copergas	0.53	0.47	0.52	0.14	0.19	0.47	0.17

Table 1.1: Natural gas production and distribution costs parameters adjusted for each LDC.

- Natural gas price (p)

The average value for the volume (in m³) of natural gas purchased by each LDC was used. This value is given by total purchases over total volume.

- Unit cost of natural gas production (z_p)

The sale of natural gas to LDCs in different states is carried out by Petrobras. Therefore, I considered the natural gas production sector to be the part of Petrobras' operation related to the sale of natural gas. As a simplifying hypothesis, I assumed that Petrobras' profit margin with natural gas sales is the same for all states. Such margin is given by the

[5] In 2018, CEG, CEG Rio and Gas Natural Fenosa became controlled by the same holding company, and were renamed Naturgy. To refer to each one of these companies I use the names Naturgy Rio Capital, Naturgy Rio Interior and Naturgy Sao Paulo, respectivelly.

[6] In 2020, the distribution of natural gas in Esp rito Santo started to be carried out by ESGas, no longer BR Distribuidora. Still, I use information from BR Distribuidora in order to adjust the model for ESGas.

net profit to gross revenue ratio, but only relative to Petrobras' natural gas operation. In the model, this ratio is equal to $\frac{p \quad z_p}{z_p}$, so I could freely adjust z_p to get it.

- Unit cost of natural gas distribution for each sector i (z_i)

I decomposed the unit distribution cost into $z_i = z^d + z_i^{nd}$, where z^d represents the unit direct cost and z_i^{nd} the unit indirect cost. The direct cost is given by the difference between net revenue and gross profit, although the net revenue in this case is not the accounting net revenue, but the gross revenue minus purchase of gas minus tax. Dividing the direct cost by total volume of natural gas gets us z^d. This way, unitary direct cost is the same for all sectors. Indirect cost is defined here as the difference between gross profit and net profit, representing non-operating costs and expenses. The assumption here is that the indirect cost is not proportional to the volume of natural gas sold to the sector i, but proportional to the gross profit of that sector.[7] After sharing the indirect cost among different sectors, z_i^{nd} is given by the ratio between indirect costs and volume sold to sector i.

For all LDCs it was observed that the largest unit distribution costs are attributed to residential and commercial. This is in line with what was expected, as these segments have a large number of individual customers with an average natural gas consumption much lower than the electrical and industrial sectors, implying a smaller scale gain.[8]

- Value-added tax (τ)

The rate of state value-added tax (ICMS) was used as the value for τ. Table 1.2 lists these rates for each state.

[7] The hypothesis of indirect cost proportional to the volume of gas would give us z_i equal for all sectors. However, for some LDCs this would lead to the occurrence of negative net pro t for sectors with lower pro t margins, such as the electrical and industrial sectors.

[8] Between 2014 and 2019, Sulgas, SCGas, Gas Brasiliano and Naturgy São Paulo did not sell to the electricity sector. In the case of these LDCs, I assumed that sales to the electricity sector remained zero in the experiments.

State	Tax rate (%)
RS	0.18
SC	0.17
PR	0.18
SP	0.18
RJ	0.20
MG	0.18
ES	0.17
MS	0.17
BA	0.18
PE	0.18

Table 1.2: Value-added tax (ICMS) rates for each state.

- Federal and state government shareholdings in gas production and distribution (π_p^f,π_d^f,π_d^e)

In the case of the natural gas producer, I used the federal government's share of Petrobras' total capital. In the case of LDCs, federal participation is through Petrobras, so it is necessary to multiply Petrobras' participation in the company by the federal participation in Petrobras to obtain the federal participation in the LDC. State participation in LDCs occurs both directly and through state mixed capital companies. The ownership distribution for each LDC is summarized in Table 1.3.

Company	Shareholders participation (%)		
	Federal	State	Others
Petrobras	46.3	0.0	53.7
Sulgás	22.7	51.0	26.3
SCGás	19.0	3.4	77.6
Compagás	11.3	15.8	72.9
Comgás	0.0	0.0	100.0
Gás Brasiliano	23.6	0.0	76.4
Naturgy São Paulo	0.0	0.0	100.0
Naturgy Rio Capital	0.0	0.0	100.0
Naturgy Rio Interior	0.0	0.0	100.0
Gasmig	0.0	17.0	83.0
ESGás	22.7	51.0	26.3
MSGás	22.7	51.0	26.3
Bahiagás	19.2	17.0	63.8
Copergás	19.2	17.0	63.8

Table 1.3: Ownership of natural gas production and distribution companies.

1.3.2 Adjustment of natural gas demand parameters

As can be observed in Equations 1.1 and 1.2, the mark-up μ_i, which is applied to costs in order to obtain the tariff value t_i, is entirely determined by natural gas demand elasticity of substitution ρ_i. Table 1.4 presents the values of sectorial average tariffs.

LDC	Average sectorial tariffs (R$/m³)				
	residential	electrical	industrial	commercial	others
	t_0	t_1	t_2	t_3	t_4
Sulgás	5.08	-	1.23	3.27	1.06
SCGás	2.85	-	1.44	2.10	1.37
Compagás	2.84	1.72	1.65	2.31	1.59
Comgás	5.98	1.22	1.51	3.50	1.25
Gás Brasiliano	6.54	-	1.79	3.37	1.55
Naturgy São Paulo	3.71	-	1.72	2.99	1.48
Naturgy Rio Capital	6.53	0.65	1.65	3.25	1.93
Naturgy Rio Interior	2.67	0.96	1.03	2.00	1.00
Gasmig	3.57	1.81	1.67	2.66	2.09
ESGás	4.36	1.28	1.28	2.09	1.26
MSGás	1.28	0.53	0.79	1.14	0.65
Bahiagás	3.17	1.33	1.48	1.78	1.49
Copergás	2.15	0.74	0.91	1.95	0.84

Table 1.4: Average sectorial tariffs for each LDC.

- Sector i elasticity of substitution (ρ_i)

Based on Equation (1.1), we see that LDCs adjust sectorial tariffs by applying a mark-up μ_i over unit cost. At this mark-up there is a single corresponding value for the elasticity of substitution ρ_i, as in Equation (1.2). Therefore, I selected the value of ρ_i such that sectorial tariffs t_i are equal to the values observed in data. The elasticities obtained are summarized in Table 1.5.

A certain stability was observed in the elasticities values for residential and commercial sectors across different states, as opposed to what happen with the remaining sectors, especially with electricity sector. The explanation for this fact is that the profit margin of the first two sectors is higher, which is reflected in an also higher mark-up and, therefore, in a lower elasticity. In the case of electricity sector, the mark-up is very close to unity, making this elasticity value very sensitive. The main reason for it is because the electrical sector is very subject to sudden changes in volumes and revenues due to the small number of clients, usually only a few thermoelectric power plants, each with specific contracts regarding energy tariffs. Still, they usually represent a large share of the market, so it is hard not to take then into consideration in the adjustment.

LDC	Sectorial elasticities of substitution				
	residential	electrical	industrial	commercial	others
	ρ_0	ρ_1	ρ_2	ρ_3	ρ_4
Sulgás	2.66	-	9.64	3.05	22.41
SCGás	5.81	-	25.17	8.08	36.97
Compagás	2.67	11.03	15.80	3.65	31.76
Comgás	3.03	114.95	11.48	3.68	53.97
Gás Brasiliano	1.92	-	8.97	2.65	36.70
Naturgy São Paulo	4.33	-	13.93	5.05	41.04
Naturgy Rio Capital	4.33	52.08	16.53	5.80	19.10
Naturgy Rio Interior	3.99	30.99	18.89	4.78	23.37
Gasmig	3.12	10.23	16.19	4.13	6.27
ESGás	3.17	38.40	39.77	5.43	56.75
MSGás	4.06	57.95	6.90	4.41	10.80
Bahiagás	2.60	99.09	13.43	5.74	12.32
Copergás	2.20	19.60	6.20	2.30	8.18

Table 1.5: Sectorial elasticities of substitution for each LDC.

1.3.3 Adjustment of productive and residential sectors parameters

Unlike the natural gas sector, it was not possible to calculate parameter values directly from the data for productive and residential sectors, so I needed to adjust them through numerical calibration. I used natural gas volumes distributed for each sector (Table 1.6) as target statistics in adjusting parameters $A, \alpha_1, \ldots, \alpha_4$. The relative participation of each productive sector in GDP, obtained through data from the Regional Accounts System (SCR) of the Brazilian statistics office (IBGE), guided the adjustment of the weights $\beta_1, \ldots, \beta_4$ (Table 1.7). In the case of the representative consumer from the residential sector, I calibrated ψ to adjust the GDP (Table 1.8). As for the parameter θ, I used the inverse of the Frisch elasticity of labor supply. The value used was 0.246, the same found for Brazil by Moura (2015).

LDC	Daily volume by sector (thousand m³)				
	residential	electrical	industrial	commercial	others
Sulgas	12	0	1,499	31	422
SCGas	4	0	1,410	15	299
Compagas	24	591	846	16	396
Comgas	676	1,476	10,359	386	576
Gas Brasiliano	5	0	704	7	32
Naturgy Sao Paulo	17	0	1,054	16	38
Naturgy Rio Capital	306	4,706	1,337	224	2,344
Naturgy Rio Interior	13	5,519	1,760	10	613
Gasmig	9	888	2,427	32	100
ESGas	10	992	1,824	8	129
MSGas	2	1,362	370	5	13
Bahiagas	14	90	3,358	36	229
Copergas	7	2,943	1,094	11	202

Table 1.6: Daily sectorial volumes of natural gas by LDC (thousand m³ per day).

State	Sector			
	electrical	industrial	commercial	others
RS	2.4	34.6	11.3	51.6
SC	2.7	34.6	12.8	49.8
PR	3.8	34.4	12.3	49.3
SP	1.8	31.2	11.1	55.6
RJ	2.7	17.6	8.7	70.2
MG	2.9	28.8	10.0	58.1
ES	2.4	20.2	12.1	64.7
MS	4.3	24.9	10.2	60.3
BA	3.0	31.9	9.3	55.3
PE	4.1	26.8	11.5	57.2

Table 1.7: Sector participation in GDP by state (%).

LDC	GDP (million R$)
Sulgás	731.4
SCGás	447.1
Compagás	731.4
Comgás	3,049.3
Gás Brasiliano	176.3
Naturgy São Paulo	731.4
Naturgy Rio Capital	680.4
Naturgy Rio Interior	423.6
Gasmig	961.4
ESGás	202.2
MSGás	161.8
Bahiagás	468.7
Copergás	273.1

Table 1.8: GDP of the regions supplied by each LDC

1.3.4 Numerical calibration procedure

Let $\Theta = (A, \alpha_1, \ldots, \alpha_4, \beta_1, \ldots, \beta_4, \psi)$ be the vector of parameters to be numerically calibrated. Let m_d be the target statistics vector and $m(\Theta)$ the model statistics vector. We must choose Θ so that m_d and $m(\Theta\ )$ are close. One way to do this is by minimizing the sum of squared deviation of the statistics

$$\Theta \ = \arg\min \left(m(\Theta) \quad m_d\right)^T W \left(m(\Theta) \quad m_d\right)$$

where W is a weight matrix.

Table 1.9 describes the values obtained with the calibration procedure for each LDC, while Table 1.10 summarizes deviations between model and data moments. We can see that the relative deviations are small, reaching the maximum value of only 3.22% for the participation of the commercial sector for Comgás. On average, deviations are below 1%.

LDC	Adjusted parameters									
	A	α_1	α_2	α_3	α_4	β_1	β_2	β_3	β_4	ψ
Sulgas	47	0	0.06	0.03	0.06	0.11	0.32	0.2	0.37	8.1E-7
SCGas	40	0	0.11	0.08	0.11	0.16	0.28	0.23	0.3	1.4E-6
Compagas	87	0.06	0.05	0.02	0.05	0.14	0.31	0.2	0.35	1.7E-5
Comgas	76	0.05	0.05	0.04	0.05	0.12	0.3	0.21	0.36	2.6E-8
Gas Brasiliano	73	0	0.06	0.02	0.06	0.07	0.32	0.18	0.43	3.9E-3
Naturgy São Paulo	53	0	0.09	0.05	0.08	0.15	0.3	0.22	0.32	1.1E-6
Naturgy Rio Capital	63	0.04	0.08	0.1	0.09	0.15	0.25	0.22	0.35	3E-6
Naturgy Rio Interior	39	0.09	0.08	0.04	0.07	0.16	0.26	0.21	0.36	2.5E-6
Gasmig	65	0.08	0.07	0.03	0.04	0.14	0.29	0.2	0.36	1.3E-6
ESGas	52	0.08	0.08	0.04	0.08	0.13	0.26	0.22	0.38	2.4E-4
MSGas	32	0.06	0.05	0.03	0.04	0.18	0.27	0.21	0.33	3.9E-5
Bahiagas	57	0.08	0.07	0.04	0.06	0.12	0.31	0.19	0.38	1.3E-5
Copergas	43	0.06	0.05	0.01	0.04	0.12	0.29	0.19	0.4	3.4E-5

Table 1.9: Adjusted parameters by LDC.

LDC	Relative deviation (%)	
	average	maximum
Sulgás	0.15	1.00
SCGás	0.08	0.28
Compagás	0.04	0.20
Comgás	1.16	3.22
Gás Brasiliano	0.07	0.37
Naturgy São Paulo	0.04	0.12
Naturgy Rio Capital	0.11	0.74
Naturgy Rio Interior	0.15	0.88
Gasmig	0.12	0.50
ESGás	0.14	0.94
MSGás	0.05	0.32
Bahiagás	0.11	0.57
Copergás	0.11	0.62

Table 1.10: Average and maximum relative deviations for the calibrated moments by LDC.

1.4 Numerical Experiments

In what follows I describe the procedure and results of some numerical counterfactual experiments using the model with parameters adjusted for each LDC. The first experiment involves the privatization of 8 LDC that currently have state participation. The second experiment assesses the impacts, on all 13 LDCs considered, of a reduction in the price of the natural gas purchased by LDCs.

1.4.1 Privatization of LDCs

I assessed the minimum efficiency gain needed so that, from a state level fiscal point of view, the privatization of the LDC is advantageous. In order to calculate this efficiency threshold, starting with the adjusted model, I first reset state and federal participation in the company. Then, numerically, a fixed percentage of reduction is applied to the distribution costs for all sectors in such a way that the state government revenue in the new equilibrium is the same as the one obtained with the calibrated model.[9] With this approach, I do not discuss whether or not privatization do bring efficiency gains, or if there are differences in the objective function between private and state-owned companies. What I look for is a sort of ”equilibrium efficiency gain”.

Table 1.11 describes the cost reduction obtained for each of the 8 LDCs analyzed that have some state government ownership. With the exception of Sulgás (RS), all LDCs required a cost reduction of less than 10%, while the value for SCGás (SC) was of only 0.2%. One way to interpret those numbers is that they give a measure of how easy it is for the privatization to be advantageous, at least in a fiscal sense. The lower the unitary cost reduction, the easier it is for efficiency gains to make it advantageous.

LDC	Unitary cost reduction (%)
Sulgás	22.9
SCGás	0.2
Compagás	2.5
MGasmig	4.7
ESGás	3.4
MSGás	9.1
Bahiagás	4.1
Copergás	5.5

Table 1.11: Minimum unitary distribution cost reduction needed for state-level fiscal balance, for each LDC.

The magnitude of the efficiency gain necessary is directly related to both LDC’s profitability and the size of the state’s ownership over the company. Figure 1.1 illustrates this point. On the horizontal axis we have the fraction of gross revenue that is converted into dividends for the state government, that is, the product of profitability and state’s participation. On the vertical axis we have the efficiency gain. The necessary efficiency gain is, on average, around 4.5% for each percentage point of revenue reverted to dividends to the state.

[9] The revenue that the states would obtain from the privatization of the LDC is not considered in the experiment.

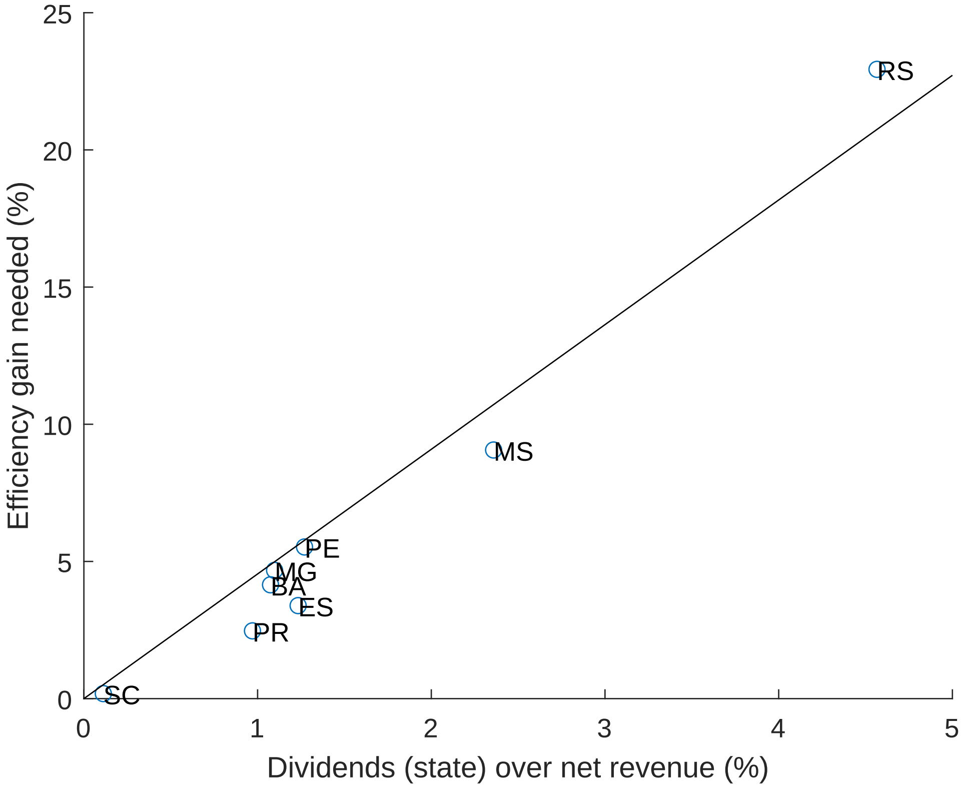

Figure 1.1: Dividends received by the state as a fraction of the LDC's revenue versus minimum efficiency gain needed in privatization.

However, the way in which efficiency gains in distribution spread throughout the economy and impacts tax collection is specific to each state. In Figure 1.2 shows the contribution of each productive sector in changes of tax revenue. For each state, the sum of sectorial contributions is equal to 100%. There is clear heterogeneity in both magnitude and direction of each contribution. For example, in some states there is an increase in tax revenue over the industrial sector, while in others there is a decrease. In addition, although the contribution of the tax revenue increase over the LDC is expressive, which is to be expected since the effects of efficiency gains occur directly upon it, we still observe that the contribution from other sectors are more significant, even if they are impacted only indirectly through reduction of natural gas tariffs. This highlights the importance of general equilibrium effects in studying tax revenue effects in such counterfactual scenarios.

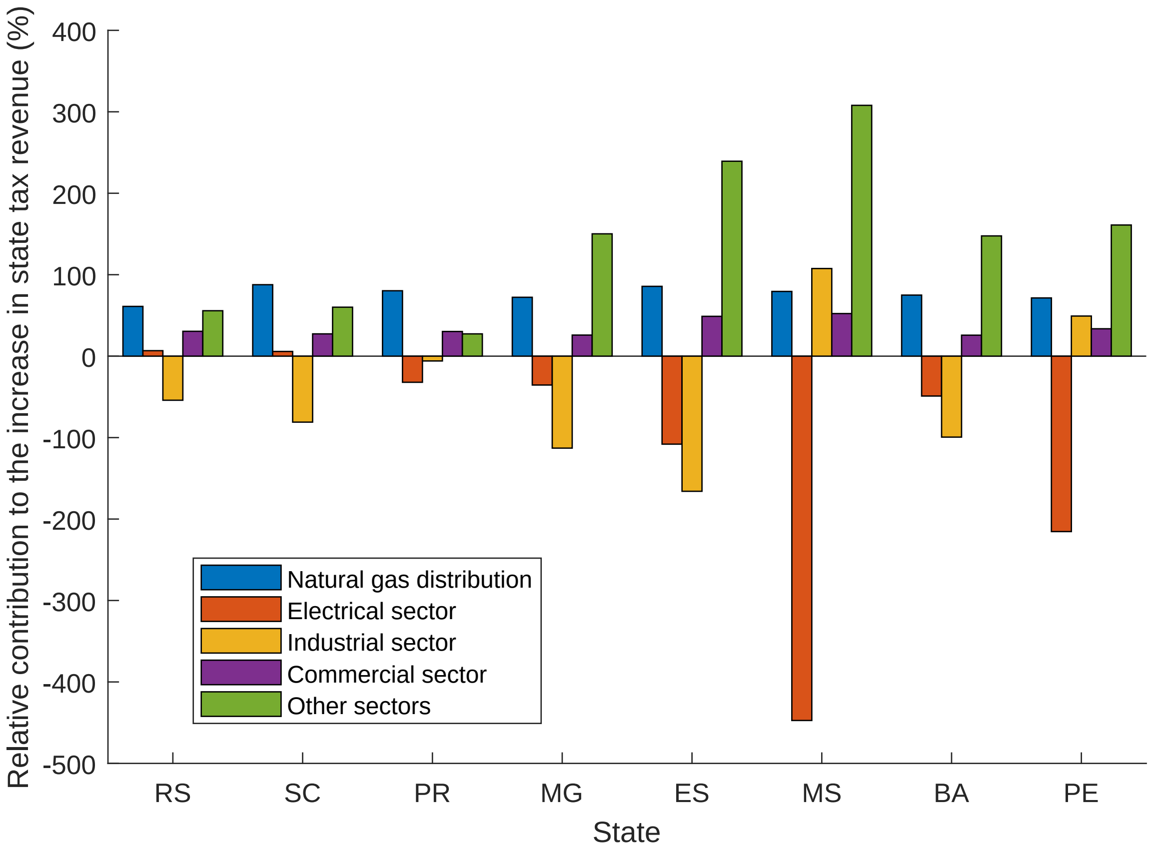

Figure 1.2: Breakdown of the relative contribution of each sector to the increase in state tax revenue.

1.4.2 Increased competition in natural gas production

Within the discussion of the New Gas Law, there is an expectation of increased competition in gas production. In this context, I carried out an experiment that assesses the impact of a reduction in the price of natural gas purchased by LDCs upon the volume consumed, as well as upon regional economies. According to data on natural gas production, currently monopolized by Petrobras, the profit margin of the activity is of approximately 10%. As a way of representing an increase in competition within gas production, I considered an intermediate reduction of 5% in the natural gas price parameter p, which would represent a reduction by half of the profit margin while maintaining the unitary production cost parameter z_p constant. In addition to the LDCs considered in the previous privatization experiment, I also included the already private LDCs from São Paulo (Comgás, Gás Brasiliano and Naturgy São Paulo) and Rio de Janeiro (Naturgy Rio Capital and Naturgy Rio Interior).

LDC	Tariff changes (%)				
	residential	electrical	industrial	commercial	others
Sulgás	-1.3	-	-3.8	-1.9	-4.2
SCGás	-1.9	-	-3.2	-2.4	-3.4
Compagás	-3.0	-3.4	-3.4	-3.1	-3.4
Comgás	-0.9	-3.0	-2.6	-1.4	-3.0
Gás Brasiliano	-1.6	-	-3.2	-2.4	-3.3
Naturgy São Paulo	-1.7	-	-3.1	-2.1	-3.4
Naturgy Rio Capital	-0.8	-6.3	-2.6	-1.5	-2.2
Naturgy Rio Interior	-1.9	-4.1	-4.0	-2.4	-4.0
Gasmig	-2.4	-3.6	-3.7	-2.9	-3.3
ESGás	-1.7	-4.0	-4.0	-2.9	-4.0
MSGás	-2.3	-4.3	-3.3	-2.5	-3.8
Bahiagás	-2.6	-3.8	-3.7	-3.4	-3.7
Copergás	-2.3	-3.8	-3.5	-2.4	-3.6
Average	-1.9	-4.3	-3.4	-2.4	-3.5

Table 1.12: Relative changes in sectorial tariffs after a 5% reduction in natural gas price.

The effect of price change upon tariffs is shown in Table 1.12. For almost all sectors and LDCs, the tariff reduction was below 5%. In the model, the value of tariffs are not affected by general equilibrium effects, being determined directly as in Equation 1.1.

LDC	Total volume	Tax revenue	GDP
Sulgás	69	0.03	0.08
SCGás	150	0.12	0.3
Compagás	91	0.06	0.14
Comgás	308	0.27	0.6
Gás Brasiliano	42	0.06	0.11
Naturgy São Paulo	63	0.03	0.06
Naturgy Rio Capital	629	-0.24	2.04
Naturgy Rio Interior	159	0.28	1.05
Gasmig	72	0.06	0.16
ESGás	372	0.66	2.5
MSGás	661	0.25	1.35
Bahiagás	165	0.21	0.65
Copergás	77	0.13	0.33
Average	220	0.15	0.72

Table 1.13: Relative changes after a 5% reduction in natural gas price (%).

On average, the volume consumed doubled with price reduction, with a minimum increase of 42% for Gás Brasiliano and a maximum of 629% for Naturgy Rio Capital. Table 1.13 describes the values for all LDCs. In the case of GDP and tax revenue, an average increase of 0.72% and 0.15%, respectively, was observed. Considering that the natural gas sector is very small compared to the rest of the economy, such increases are significant. On in the case of Naturgy Rio Capital, which supplies the metropolitan region of Rio de Janeiro, the impact on GDP was more significant, around 2%.

LDC	Relative changes in volumes (%)				
	residential	electrical	industrial	commercial	others
Sulgás	4	-	45	6	159
SCGás	12	-	129	22	254
Compagás	9	46	73	13	204
Comgás	3	2,377	37	6	413
Gás Brasiliano	3	-	33	7	245
Naturgy São Paulo	8	-	55	11	322
Naturgy Rio Capital	6	1,145	59	11	58
Naturgy Rio Interior	9	172	116	14	167
Gasmig	8	45	85	13	24
ESGás	8	274	386	20	973
MSGás	11	842	28	14	54
Bahiagás	8	4,215	66	23	60
Copergás	6	100	25	6	36
Average	7	1,024	88	13	228

Table 1.14: Relative changes in sectorial volumes after a 5% reduction in natural gas price.

The changes in volumes consumed by different sectors are strongly associated with elasticity of substitution values, shown for each LDC and sector in Table 1.5. While for the residential sector average increase in volume was of only 7%, in the case of the electricity sector, with much greater elasticity, natural gas consumption was 10 times higher on average. Table 1.14 reports the increases in volumes.

LDC	Changes in sectorial revenues (%)			
	electrical	industrial	commercial	others
Sulgás	0.07	0.09	0.07	0.07
SCGás	0.24	0.36	0.25	0.27
Compagás	0.22	0.14	0.13	0.13
Comgás	1.16	0.61	0.58	0.58
Gás Brasiliano	0.1	0.13	0.1	0.1
Naturgy São Paulo	0.05	0.08	0.05	0.05
Naturgy Rio Capital	8.58	1.89	1.84	1.85
Naturgy Rio Interior	4.61	1.06	0.91	0.92
Gasmig	0.33	0.19	0.14	0.14
ESGás	4.12	2.81	2.36	2.37
MSGás	3.23	1.29	1.26	1.26
Bahiagás	0.83	0.71	0.62	0.62
Copergás	0.78	0.33	0.31	0.31
Average	1.87	0.75	0.66	0.67

Table 1.15: Relative changes in sectorial revenues after a 5% reduction in natural gas price

To better understand the impact of price reduction upon GDP, the sectorial revenues variations can be found in Table 1.15. The electrical sector is the one with the largest increase in revenue, of 1.87% on average. The other sectors have an increase in GDP that are lower and closer to each other, with the industrial sector being the second with the highest increase, 0.75% on average. In the case of LDCs without sales to the electricity sector (Sulgás, SCGás, Gás Brasiliano and Naturgy São Paulo), the industrial sector is the one displaying the largest increase.

1.5 Concluding Remarks

In this article, I developed a structural economic model to assess the impacts that reforms in the Brazilian natural gas sector may have on state-level economies, with greater emphasis on the natural gas distribution sector. I calibrated the model for 13 of the major Brazilian LDCs, taking into account both financial and operational data of these companies, as well as economic data from the regions where they operate.

A median of 4.4% in the need for efficiency gains by LDCs to make their privatization advantageous from a state-level fiscal point of view was observed. There was also an average increase of 0.72% in GDP as a response to a 5% reduction in the price of natural gas purchased by LDCs. In both experiments, there was significant heterogeneity in the results for different LDCs and regions.

A potential extension of the work developed here is to study the dynamic behavior in response to reforms in the natural gas sector. In the short run, a lower elasticity of demand is expected due to the difficulty of substituting gas for other energy sources. In addition, short run supply is limited by the extent of the existing distribution network.

Bibliography

[1] Sami Alpanda and Adrian Peralta-Alva. “Oil crisis, energy-saving technological change and the stock market crash of 1973–74”. Review of Economic Dynamics 13.4 (2010), pp. 824–842.

[2] Benjamin S Cheng. “Energy consumption and economic growth in Brazil, Mexico and Venezuela: a time series analysis”. Applied Economics Letters 4.11 (1997), pp. 671–674.

[3] Steve Cicala. “When does regulation distort costs? lessons from fuel procurement in us electricity generation”. American Economic Review 105.1 (2015), pp. 411–44.

[4] Empresa de Pesquisa Energéticas EPE. “Balanço Energético Nacional 2020-Ano base 2019”. Rio de Janeiro (2020).

[5] Li Fei et al. “Energy consumption-economic growth relationship and carbon dioxide emissions in China”. Energy policy 39.2 (2011), pp. 568–574.

[6] Helder Queiroz Pinto Junior and Edmar Fagundes de Almeida. Economia da energia: fundamentos Elsevier, 2007.

[7] Fernando I Leal, Erik E Rego, and Celma de Oliveira Ribeiro. “Natural gas regulation and policy in Brazil: Prospects for the market expansion and energy integration in Mercosul”. Energy Policy 128 (2019), pp. 817–829.

[8] Renuka Mahadevan and John Asafu-Adjaye. “Energy consumption, economic growth and prices: A reassessment using panel VECM for developed and developing countries”. Energy policy 35.4 (2007), pp. 2481–2490.

[9] Melissa Cristina Mathias and Alexandre Szklo. “Lessons learned from Brazilian natural gas industry reform”. Energy Policy 35.12 (2007), pp. 6478–6490.

[10] Guilherme V Moura. “Multiplicadores fiscais e investimento em infraestrutura”. Revista Brasileira de Economia 69.1 (2015), pp. 75–104.

[11] Alexander Cotte Poveda and Clara Inés Pardo Martínez. “Trends in economic growth, poverty and energy in Colombia: long-run and short-run effects”. Energy Systems 2.3 (2011), pp. 281–298.

[12] Martín A Rossi. “Technical change and efficiency measures: the post-privatisation in the gas distribution sector in Argentina”. Energy Economics 23.3 (2001), pp. 295–304.

[13] Hadi Sasana. “The impact of fossil and renewable energy consumption on the economic growth in Brazil, Russia, India, China and South Africa” (2017).

[14] Ugur Soytas and Ramazan Sari. “Energy consumption, economic growth, and carbon emissions: challenges faced by an EU candidate member”. Ecological economics 68.6 (2009), pp. 1667–1675.

[15] David I Stern. “The role of energy in economic growth”. International energy and poverty (2015), pp. 35–47.

[16] Zhang Zhixin and Ren Xin. “Causal relationships between energy consumption and economic growth”. Energy Procedia 5 (2011), pp. 2065–2071.

1.A Finding the Equilibrium

Despite, for a general set of parameters, not being possible to determine the equilibrium analytically, it is possible to analytically represent all equilibrium objects as a function of only the salary w, given the parameters. This considerably simplifies the numerical effort as it turns it into an equivalent one-dimensional problem.

1.A.1 Prices

Given that, for all sectors of the economy, the price elasticity of natural gas demand is constant and independent of the tariff ($\varepsilon(t_i) = \rho_i$), by Equations (1.2) and (1.1) we have

$$\mu_i = \frac{\rho_i}{\rho_i \quad 1} \quad i = 0, \ldots, J \tag{1.16}$$

$$t_i = \mu_i \left(p + \frac{z_i}{1 - \tau} \right) \quad i = 0, \ldots, J \tag{1.17}$$

Solving (1.5) for g_j, (1.6) for l_j, substituting both expressions in (1.4) and doing some algebraic manipulations, we get p_j as a function of w

$$p_j\left(w\right) = \left(\alpha_j^{\rho_j} t_j^{1-\rho_j} + \left(1 - \alpha_j\right)^{\rho_j} \left(\frac{w}{1 - \tau} \right)^{1-\rho_j} \right)^{\frac{1}{1-\rho_j}} \quad j = 1, \ldots, J \tag{1.18}$$

Similarly, for the final consumption good sector, solving for g_0 and c_j in (1.8) and (1.9), replacing them in Equation (1.7), gives us the relationship

$$A^{1-\rho_0} = \left(1 - \sum_{j=1}^{J} \beta_j \right)^{\rho_0} t_0^{1-\rho_0} + \sum_{j=1}^{J} \beta_j^{\rho_0} p_j\left(w\right)^{1-\rho_0} \tag{1.19}$$

Notice that the only unknown in Equation (1.19) is w. Although it is not generally possible to analytically solve this equation for w, it can be easily solved numerically.

1.A.2 Allocations as functions of w

Labor supply, l, is already a function of w by Equation (1.12)

$$l(w) = \left(\frac{w}{\psi} \right)^{\frac{1}{\theta}} \tag{1.20}$$

By manipulating Equation (1.9), replacing the market clearing conditions for intermediate goods markets, $c_j = y_j$, we get

$$y_j = A^{\rho_0 - 1} \left(\frac{\beta_j}{p_j} \right)^{\rho_0} y \quad j = 1, \ldots, J \tag{1.21}$$

Solving Equation (1.6) for l_j and substituting y_j by the expression in (1.21)

$$l_j = A^{\rho_0 - 1} \left(1 - \alpha_j\right)^{\rho_j} \left(\frac{\left(1 - \tau\right) p_j}{w} \right)^{\rho_j} \left(\frac{\beta_j}{p_j} \right)^{\rho_0} y \quad j = 1, \ldots, J \tag{1.22}$$

Substituting (1.22) and (1.20) in the market clearing condition for the labor market, $\sum_{j=1}^{J} l_j = l$, we find an explicit expression for $y\left(w\right)$, given by

$$y(w) = \frac{l(w)}{A^{\rho_0 - 1} \sum_{j=1}^{J} (1 - \alpha_j)^{\rho_j} \left(\frac{(1-\tau) p_j(w)}{w} \right)^{\rho_j} \left(\frac{\beta_j}{p_j(w)} \right)^{\rho_0}} \tag{1.23}$$

Therefore, y_j and l_j as functions of w become

$$y_j(w) = A^{\rho_0 - 1} \left(\frac{\beta_j}{p_j(w)} \right)^{\rho_0} y(w) \quad j = 1, \ldots, J \tag{1.24}$$

$$l_j(w) = A^{\rho_0 - 1} (1 - \alpha_j)^{\rho_j} \left(\frac{(1 - \tau) p_j(w)}{w} \right)^{\rho_j} \left(\frac{\beta_j}{p_j(w)} \right)^{\rho_0} y(w) \quad j = 1, \ldots, J \tag{1.25}$$

By solving (1.8) and (1.5) for g_0 and g_j, we get that the demands and total supply of natural gas are

$$g_0(w) = A^{\rho_0 - 1} \left(\frac{1 - \sum_{j=1}^{J} \beta_j}{t_0} \right)^{\rho_0} y(w) \tag{1.26}$$

$$g_j(w) = \left(\frac{\alpha_j p_j(w)}{t_j} \right)^{\rho_j} y_j(w) \quad j = 1, \ldots, J \tag{1.27}$$

$$g(w) = g_0(w) + \sum_{j=1}^{J} g_j(w) \tag{1.28}$$

The remaining allocations are easily obtained from the remaining equilibrium conditions. Table 1.16 summarizes all expressions.

$\mu_i = \frac{\rho_i}{\rho_i - 1} \quad i = 0, \dots, J$
$t_i = \mu_i \left(p + \frac{z_i}{1 - \tau} \right) \quad i = 0, \dots, J$
$p_j(w) = \left(\alpha_j^{\rho_j} t_j^{1-\rho_j} + (1 - \alpha_j)^{\rho_j} \left(\frac{w}{1-\tau} \right)^{1-\rho_j} \right)^{\frac{1}{1-\rho_j}} \quad j = 1, \dots, J$
$l(w) = \left(\frac{w}{\psi} \right)^{\frac{1}{\theta}}$
$y(w) = \frac{l(w)}{A^{\rho_0 - 1} \sum_{j=1}^{J} (1 - \alpha_j)^{\rho_j} \left(\frac{(1-\tau) p_j(w)}{w} \right)^{\rho_j} \left(\frac{\beta_j}{p_j(w)} \right)^{\rho_0}}$
$y_j(w) = A^{\rho_0 - 1} \left(\frac{\beta_j}{p_j(w)} \right)^{\rho_0} y(w) \quad j = 1, \dots, J$
$c_j(w) = y_j(w) \quad j = 1, \dots, J$
$l_j(w) = A^{\rho_0 - 1} (1 - \alpha_j)^{\rho_j} \left(\frac{(1-\tau) p_j(w)}{w} \right)^{\rho_j} \left(\frac{\beta_j}{p_j(w)} \right)^{\rho_0} y(w) \quad j = 1, \dots, J$
$g_0(w) = A^{\rho_0 - 1} \left(\frac{1 - \sum_{j=1}^{J} \beta_j}{t_0} \right)^{\rho_0} y(w)$
$g_j(w) = \left(\frac{\alpha_j p_j(w)}{t_j} \right)^{\rho_j} y_j(w) \quad j = 1, \dots, J$
$g(w) = g_0(w) + \sum_{j=1}^{J} g_j(w)$
$\Pi_p(w) = (p - z_p)\, g(w)$
$\Pi_d(w) = (\mu_0 - 1)\left[(1-\tau)p + z_d\right] g_0(w) + \sum_{j=1}^{J} (\mu_j - 1)\left[(1-\tau)p + z_d\right] g_j(w)$
$T(w) = \pi_d^e \Pi_d(w) + \tau_e \left\{ (t_0 - p)\, g_0(w) + \sum_{j=1}^{J} \left[p_j(w)\, y_j(w) - p g_j(w) \right] \right\}$
$c(w) = wl(w) + T(w) + \left(1 - \pi_p^f\right) \Pi_p(w) + \left(1 - \pi_d^e - \pi_d^f\right) \Pi_d(w)$
$K_p(w) = z_p g(w)$
$K_d(w) = \sum_{i=0}^{J} z_i g_i(w)$
$c_f(w) = \pi_p^f \Pi_p(w) + \pi_d^f \Pi_d(w)$

Table 1.16: Equilibrium prices and allocations as functions of the wage rate w.

Chapter 2

Impacts of the New Brazilian Gas Law Over Natural Gas Distribution Companies and Local Economies

Abstract

This paper investigates how increasing competition in the natural gas production sector would impact natural gas local distribution companies (LDC) and regional economies over time. I develop a structural dynamic model with monopolistic supply of natural gas by a LDC facing a capacity constraint changeable through investment over time, as well as a production sector that uses capital and competing energy sources along with labor. The model is adjusted for 12 of the major Brazilian LDCs using financial and operational data along with regional economic data. I found out that a 5% natural gas price decrease leads to large increases in natural gas consumption, with median value of 80% among the LDCs. Much of this increase happens in the short run. However, increases are much smaller when other competing energy sources have their price reduced as well, but only in the long run.

2.1 Introduction

One of the goals of the recently sanctioned Brazilian New Gas Law is to promote the expansion of the natural gas distribution network. With the end of Petrobras' monopoly over natural gas production and transportation, an increase in competition would reduce the price of it, leading to increased demand. Natural gas distribution is performed by local distribution companies (LDC, henceforth), with each one of them holding monopoly over the consumers of a particular geographic location.

I developed a structural dynamic model in order to study how changes in the natural gas production sector would impact natural gas distribution and regional economies over time. The LDC is a classical monopolistic company facing a capacity constraint, deciding at each period the tariff charged for each unit of natural gas distributed, as well as the investment in capacity expansion. There is a productive sector, composed of intermediary and final firms, that uses labor, capital and energy from different sources to produce a final consumption good. Distinct types of capital are associated with each energy source, and their stocks are held by capital producers that rent them to the production sector. There is also a representative household that supplies labor and consumes final good. The model parameters are adjusted for 12 LDCs and their regional economies, selected based on data availability and quality. I used financial and operational indicators, along with some regional macroeconomic statistics, as targets for the calibration.

The main advantage of using a dynamic framework, instead of a static one, is to be able to model investment decisions in a more realistic way, that is, a monopolist LDC does not only determines the tariff based on the demand curve and operational costs. It also considers the funding of an investment schedule into the tariff. This allows us to investigate not only the impacts of some structural changes not only in the long run, but also in the short run.

I found out that a 5% decrease in natural gas price, keeping other energy prices constant, leads not only to a 53% median increase in volume after 1 year, but also an 80% increase in the long run. However, the median increase in regional GDP is 0.1% in one year, dropping to only 0.02% in the long run. Those results, though, are very sensitive to simultaneous changes in the price of other energy sources.

Most of the literature about the natural gas energy industry only use reduced form and time series estimation, not a decision-theoretic approach as I did. This is true especially for Brazil. However, there are some works that proposed structural models relating to energy sources in a more general way. Alpanda and Peralta-Alva (2010) uses a general equilibrium framework to study how increases in energy cost, with technology adoption towards energy saving, causes firms market value to drop. Stern (2015) point out that energy is not usually included in mainstream economic growth models as a relevant input, while ecological economists do attribute energy a relevant role in economic growth. In fact, authors do find a positive relationship between energy consumption and economic growth.[1]

Optimal pipeline investment size under uncertainty is discussed by Bergendahl (1988), and volatility in oil and natural gas markets in Ewing, Malik, and Ozfidan (2002). Nevertheless, in my model all investment schedule is done in a deterministic setting. There are different estimates for price elasticity of natural gas demand varies above and below unity (Burke and Yang (2016); Dagher (2012)). In my model I must assume elastic demand (elasticity above unit) in order for the monopolist to set a finite tariff.

Within my knowledge, this paper is the only one in the literature at this time that models tariff and investment decisions of a monopolist LDC. I also insert this company in a semi-general equilibrium environment, that is, one where some of the prices in the economy are determined through a competitive environment where no participant is capable of setting prices, and their equilibrium values are those that equal supply and demand for some of the markets. Of course, this does not apply to natural gas tariffs as they are set by the monopolist, and neither applies to energy prices and interest rates, which are set exogenously.

2.2 Model

The following model describes a local economy, either a state or some part of it, where all natural gas is distributed by a single monopolistic company facing a capacity constraint. Raw energy from different sources are supplied by a constant exogenous price. The production sector is broken down into different competitive firms using energy, capital services and labor as inputs. Different capital types, according to the source of energy that powers it, are produced and held by capital producing firms. A representative household

[1] Sasana (2017); Cheng (1997); Poveda and Mart nez (2011); Zhixin and Xin (2011) are some examples.

supplies labor and demands final consumption good.

2.2.1 Energy production

There are two energy sources in the economy: natural gas and other sources. At each period t, any amount of raw energy demanded from both sources are supplied with exogenous prices π_t^g and π_t^e, respectively.[2] The conversion of raw energy to usable energy from other sources is direct, with any amount of usable energy sold with tariff $p_t^e = \pi_t^e$. The raw natural gas, however, need to be distributed to the production sector in order to become usable. This is done by a local distribution company (LDC) described in the next subsection.

2.2.2 Gas distribution

Natural gas distribution is done by a monopolistic company who decides at each period the tariff p_t^g charged for the gas distributed to the production sector, considering the demand curve $g_t(\cdot)$ it faces. There is a unit distribution cost of z^d. The volume of gas supplied by the LDC is limited by a capacity constraint G_t, which represents the extension of the distribution grid owned by the company. This capacity constraint can be increased or decreased at each period through investment $I_t^d = \pi^G \left[G_{t+1} - \left(1 - \delta^d\right) G_t\right]$, where δ^d is the depreciation rate and π^G is the price of the unit capacity of distribution pipelines in units of final consumption good, assumed to be constant over time. I also assume that any investment in capacity different from the depreciated value $\delta^d G_t$ implies a quadratic adjustment cost given by $\frac{\pi^G \phi^d}{2} \left(\frac{I_t^d}{\pi^G G_t} - \delta^d\right)^2 G_t$.

Given the company's objective to maximize the discounted future flow of profits, using a discount factor $\Lambda_{t+1} = \frac{1}{1+r_{t+1}}$, where r_{t+1} is the exogenous next period real interest rate[3], we can write its dynamic programming problem as follows:

[2] The use of exogenous prices here can be justified by the fact that energy prices are formed either at global level or at least national level, while the economy modeled here is regional, that is, small compared to the level where those prices are determined.

[3] As it happens to energy prices, I also assume that the local economy is small enough that it cannot influence the real interest rate, which is determined at a national or global level outside the scope of the model.

$$V_t^d\left(G_t\right) = \max_{p_t^g, I_t^d}\left(p_t^g \quad \pi_t^g \quad z^d\right) g_t\left(p_t^g\right) \quad I_t^d \quad \frac{\pi^G \phi^d}{2}\left(\frac{I_t^d}{\pi^G G_t} \quad \delta^d\right)^2 G_t$$
$$+ \Lambda_{t+1} V_{t+1}^d\left(\left(1 \quad \delta^d\right) G_t + \frac{I_t^d}{\pi^G}\right) \tag{2.1}$$

subject to investment and capacity constraints

$$I_t^d = \pi^G\left[G_{t+1} \quad \left(1 \quad \delta^d\right) G_t\right] \tag{2.2}$$

$$g_t\left(p_t^g\right) \quad G_t \tag{2.3}$$

The solution for the problem above are characterized by a monopolist tariff equation and a law of motion for G_t

$$p_t^g = \frac{\rho}{\rho \quad 1}\left(\pi_t^g + z^d + \lambda_t\right) \tag{2.4}$$

$$1 + \phi^d\left(\frac{G_{t+1}}{G_t} \quad 1\right) = \Lambda_{t+1}\left\{\frac{\phi^d}{2}\left[\left(\frac{G_{t+2}}{G_{t+1}}\right)^2 \quad 1\right] + \left(1 \quad \delta^d\right) + \frac{\lambda_{t+1}}{\pi^G}\right\} \tag{2.5}$$

where λ_t is the Lagrange multiplier associated with the capacity constraint and ρ is the price elasticity of natural gas demand.

Some interest facts about the behavior of the LDC can be found by inspecting Equations 2.4 and 2.5. When looking at the steady state, the law of motion for G_t tells us that the Lagrange multiplier must be positive, meaning the amount of natural gas supplied must be constrained at the maximum capacity. Also, when substituting $\lambda_{ss} = \pi^G\left(r_{ss} + \delta^d\right)$ in Equation 2.4 it is clear that both depreciation and opportunity cost (represented by the interest rate) must affect the tariff chosen by the monopolist. Another important characteristic of Equation 2.5 is that it is both forward and backward looking on G_t, which mean both the current and expectations over future capacities affects the current investment decision.

2.2.3 Production sector

I model the production sector using four separate firms.[4] The first two produce capital services powered by natural gas and other sources, respectively, also using different types of capital as inputs, and sell those to another firm that aggregates the individual services into a single total capital service. Lastly, a final good producer uses this total capital service along with labor to produce a final consumption good. Even though the division of the production sector into these firms is an abstraction, separating like this allows us to better analyse how each input contribute to the overall production, getting the same result as if we had a single firm taking all those inputs and producing the final consumption good. Figure 2.1 illustrates the flow of quantities between those firms.

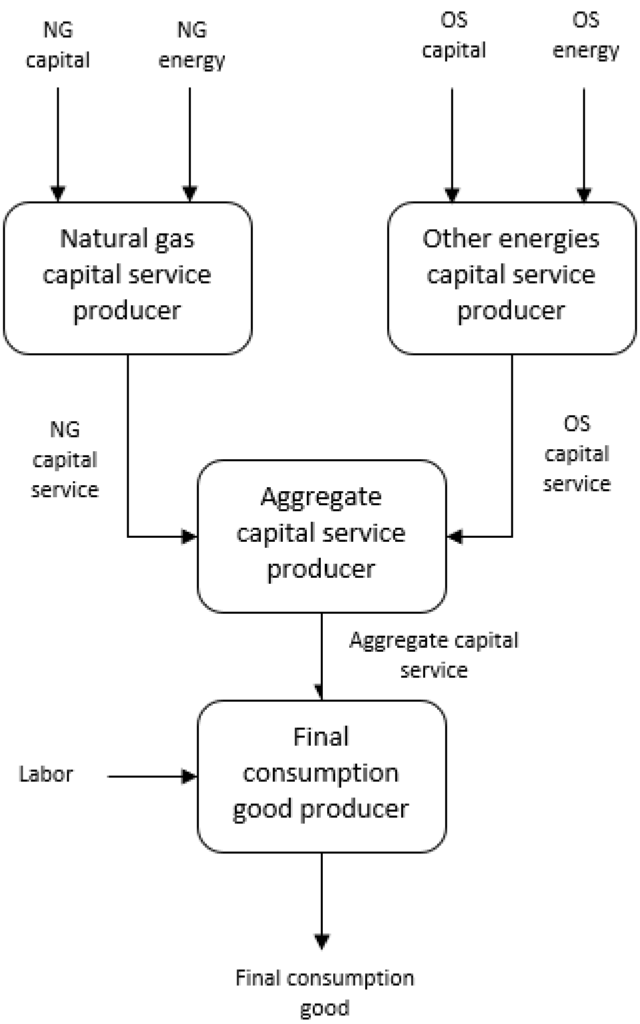

Figure 2.1: Production sector flow

[4] Since the pro t maximization problem of all rms in the production sector in each period is time independent, I dropped the time index t in this subsection for readability.

Capital service is produced by powering capital with energy. There is a single representative firm producing capital service for each energy source. Natural gas capital service production is described by a CES production function given by

$$s^g\left(k^g, g\right) = A^g\left[\alpha^g\left(k^g\right)^{\frac{\rho-1}{\rho}} + \left(1-\alpha^g\right)\left(g\right)^{\frac{\rho-1}{\rho}}\right]^{\frac{\rho}{\rho-1}} \tag{2.6}$$

where g is the volume of natural gas and k^g is the amount of rented capital powered by it.[5] Capital rental rate is r^g. Each unit of natural gas powered capital service is sold by a price q^g. Profit maximizing conditions are

$$q^g A^g\left(\frac{s^g}{A^g k^g}\right)^{\rho} = r^g \tag{2.7}$$

$$q^g A^g\left(\frac{s^g}{A^g g}\right)^{\rho} = p^g \tag{2.8}$$

As for the other sources of energy, the technology is

$$s^e\left(k^e, e\right) = A^e\left(k^e\right)^{\alpha^e}\left(e\right)^{1-\alpha^e} \tag{2.9}$$

with e being the amount of energy and k^e the amount of capital rented at a rate r^e. Capital service price is q^e. In this case, profit maximizing conditions are

$$q^e\alpha^e\frac{s^e}{k^e} = r^e \tag{2.10}$$

$$q^e\left(1-\alpha^e\right)\frac{s^e}{e} = p^e \tag{2.11}$$

A firm aggregates the different capital services into a single one using the technology

$$s\left(s^g, s^e\right) = \left[\left(s^g\right)^{\gamma} + \left(s^e\right)^{\gamma}\right]^{\frac{1}{\gamma}} \tag{2.12}$$

selling each unit of aggregate capital service for a price q. Here the optimality conditions are

[5] The monopolistic distribution company will only set a finite price in a elastic point of the demand curve, therefore it is required that $\rho > 1$. For the technologies of other firms I consider Cobb-Douglas production, as it is more convenient when adjusting the model to data.

$$q\left(\frac{s}{s^g}\right)^{1 \quad \gamma} = q^g \tag{2.13}$$

$$q\left(\frac{s}{s^e}\right)^{1 \quad \gamma} = q^e \tag{2.14}$$

Finally, a representative firm uses aggregate capital service and labor to produce a final consumption good with a Cobb-Douglas technology

$$y\left(s,n\right) = As^{\alpha}n^{1 \quad \alpha} \tag{2.15}$$

paying a wage w for each labor unit hired. Optimality conditions are

$$\alpha\frac{y}{s} = q \tag{2.16}$$

$$\left(1 \quad \alpha\right)\frac{y}{n} = w \tag{2.17}$$

2.2.4 Capital producer

For each capital type there is a representative firm that produce and hold capital, renting it to the production sector. The natural gas powered capital faces a depreciation rate δ^g over the stock held, and the production of new stock incurs in a quadratic cost of $\frac{\phi^g}{2}\left(\frac{I_t^g}{k_t^g} \quad \delta^g\right)^2 k_t^g$. The dynamic programming problem of the firm is described by

$$V_t^g\left(k_t^g\right) = \max_{I_t^g} r_t^g k_t^g \quad I_t^g \quad \frac{\phi^g}{2}\left(\frac{I_t^g}{k_t^g} \quad \delta^g\right)^2 k_t^g + \Lambda_{t+1}V_{t+1}^g\left(\left(1 \quad \delta^g\right)k_t^g + I_t^g\right) \tag{2.18}$$

subject to

$$I_t^g = k_{t+1}^g \quad \left(1 \quad \delta^g\right)k_t^g \tag{2.19}$$

The optimal path for natural gas powered capital is

$$1 + \phi^g\left(\frac{k_{t+1}^g}{k_t^g} \quad 1\right) = \Lambda_{t+1}\left\{\frac{\phi^g}{2}\left[\left(\frac{k_{t+2}^g}{k_{t+1}^g}\right)^2 \quad 1\right] + \left(1 \quad \delta^g\right) + r_{t+1}^g\right\} \tag{2.20}$$

As for the company that produces capital powered by other energy services, the description is similar, but using the superscript e:

$$I_t^e = k_{t+1}^e - (1 - \delta^e)\, k_t^e \tag{2.21}$$

$$1 + \phi^e \left(\frac{k_{t+1}^e}{k_t^e} - 1 \right) = \Lambda_{t+1} \left\{ \frac{\phi^e}{2} \left[\left(\frac{k_{t+2}^e}{k_{t+1}^e} \right)^2 - 1 \right] + (1 - \delta^e) + r_{t+1}^e \right\} \tag{2.22}$$

2.2.5 Households

Households in the economy are represented by a single representative agent that buys final consumption good and sells labor. The agent's preferences are described by a GHH utility function[6], so the optimization problem is described by

$$\max_{c,l}\, c - \psi \frac{l^{1+\theta}}{1+\theta} \tag{2.23}$$

subject to the budget constraint

$$c = wl \tag{2.24}$$

The household optimal labor supply and consumption are

$$l = \left(\frac{w}{\psi} \right)^{\theta} \tag{2.25}$$

$$c = w \left(\frac{w}{\psi} \right)^{\theta} \tag{2.26}$$

2.2.6 Equilibrium

For each period $t = 1, 2, 3, \ldots$, given exogenous interest rate and prices for raw energy inputs $(r_t, \pi_t^g, \pi_t^e)_{t=1}^{\infty}$ and initial distribution capacity and capital stocks $(G_0, k_0^g, k_0^e)_{t=1}^{\infty}$, a dynamic equilibrium for the described economy is characterized by prices $(p_t^g, p_t^e, r_t^g, r_t^e, q_t^g, q_t^e,$ $q_t, w_t)_{t=1}^{\infty}$, a series of multipliers for the capacity constraint $(\lambda_t)_{t=1}^{\infty}$ and allocations $(g_t, e_t,$ $G_t, k_t^g, k_t^e, I_t^d, I_t^g, I_t^e, s_t^g, s_t^e, s_t, n_t, y_t, c_t, l_t)_{t=1}^{\infty}$ satisfying the following conditions:

[6] The use of GHH utility function here is due to its mathematical convenience, as it provides a closed form solution for labor supply and consumption demand.

1. $p_t^e = \pi_t^e$;
2. Given the demand curve $g_t\left(\,\right)$, $\left(p_t^g, I_t^d, \lambda_{t+1}, G_{t+1}\right)$ satisfy Equations 2.2 to 2.5;
3. Given the level of natural gas powered capital service s_t^g and price q_t^g, the demand curve that the monopolist faces, $g_t\left(\,\right)$, satisfy Equation 2.8, that is, $g_t\left(p^g\right) = \frac{s_t^g}{A^g}\left(\frac{A^g q_t^g}{p^g}\right)^{\frac{1}{\rho}}$;
4. Given prices (r_t^g, p_t^g, q_t^g), (k_t^g, g_t, s_t^g) satisfy Equations 2.6 to 2.8;
5. Given prices (r_t^e, p_t^e, q_t^e), (k_t^e, e_t, s_t^e) satisfy Equations 2.9 to 2.11;
6. Given prices (q_t^g, q_t^e, q_t), (s_t^g, s_t^e, s_t) satisfy Equations 2.12 to 2.14;
7. Given prices (q_t, w_t), (s_t, n_t, y_t) satisfy Equations 2.15 to 2.17;
8. Given the rental rate r_t^g, $\left(I_t^g, k_{t+1}^g\right)$ satisfy Equations 2.19 and 2.20;
9. Given the rental rate r_t^e, $\left(I_t^e, k_{t+1}^e\right)$ satisfy Equations 2.21 and 2.22;
10. All markets clear;

2.3 Taking the Model to Data

Before using the model to analyse the impact over the natural gas distribution sector of an increase in competition in the gas production in different localities across Brazil, it is necessary to select adequate values for the parameters. These should make the model closely resemble what is observed in real world data. With that in mind, I used economic and energy consumption data from recent years, at both national and state level. I also used financial and operational information from the LDCs. The time period chosen for the adjustment is annual.

I selected 12 of the major brazilian natural gas LDCs for the study, taking into account their size and availability of financial and operational information.[7] The period of time considered is between 2014 and 2019. I obtained most of the data from financial reports, and some regarding volumes were taken from the Brazilian Association of Piped Natural Gas Distribution Companies (Abegás). This period range was selected wide enough to soften punctual fluctuations in the data, which happened eventually due to extraordinary revenues and other events, but at the same time not going too far in the past as to represent an outdated outlook of the companies.

[7] The list of selected companies is: Sulgas, SCGas, Compagas, Comgas, Gas Brasiliano, Naturgy Sao Paulo (formerly Gas Natural Fenosa), Naturgy Rio Capital (formerly CEG), Naturgy Rio Interior (formerly CEG-Rio), Gasmig, MSGas, Bahiagas and Copergas.

Most of the model parameters are directly adjusted from the data in the sense that they directly represent some moments from data. Others, on the other hand, do not map directly into observable data, and must be jointly calibrated to match some observed moments. Both groups of parameters are adjusted under the assumption of steady state equilibrium.

2.3.1 Direct adjustment of parameters

The annual depreciation rates were taken from Souza Júnior and Cornelio (2020). I set the depreciation rate of the LDC pipelines δ^d to 0.0751, reported as the value for petroleum and natural gas industry after 1973. As for the depreciation rate of both types of capital, δ^g and δ^e, the overall implicit depreciation value for capital of 0.066 was used. The real interest rate r was set to 0.033. The chosen value for capital services participation in total income α is 0.39, which is about the sum of capital service (0.35) and energy (0.04) participation in national income, according to data from the brazilian national accounts, and α^e was set to 0.9, which is the proportion of capital participation in capital services and energy. I used the inverse of the Frisch elasticity of 0.246 from Moura (2015) as the preference parameter θ. The parameters for the quadratic adjustment cost functions, ϕ^d, ϕ^g and ϕ^e, were set to 0.15, which is about the value of capital investment adjustment cost parameter estimated by Pereira (2001) for Brazil. I used the same values for the parameters described so far for every region and LDC described in this study. Table 2.1 summarizes these values.

Parameter	Value	Source
δ^d	0.075	Souza Junior and Cornelio (2020)
δ^g	0.066	Souza Junior and Cornelio (2020)
δ^e	0.066	Souza Junior and Cornelio (2020)
r	0.033	Real interest rate
α	0.391	National accounts
α^e	0.896	National accounts
θ	4.065	Moura (2015)
ϕ^d	0.3	Pereira (2001)
ϕ^g	0.3	Pereira (2001)
ϕ^e	0.3	Pereira (2001)

Table 2.1: Directly adjusted parameters common to all regions.

Data from financial and operational reports were used to adjust other LDC specific parameters. The relevant information is summarized in Table 2.2, and Table 2.3 describes the specific values for each company. The unitary cost of natural gas bought by the LDC, given by π^g in the model, is set as the average ratio between total expenditure on gas bought over total volume of gas distributed. For the unit distribution cost, I consider all costs that are not gas expenditure divided by total volume, and set the average of these ratios as the value of unit cost of distribution z^d.

In order to obtain the volume of energy from other sources, I used the average share of natural gas energy in total energy consumption, which was taken from EPE (2020). The Balance only shows data aggregated at national level, so I assume the participation of natural gas in total energy is the same within all regions. To keep consistency between energy units of different sources, values were converted to volume of gas energy equivalents (in m^3). I also considered the share of the energy sector in national GDP, assuming the same share over different regions as well. The energy sector revenue minus natural gas distribution revenue, divided by the total energy minus natural gas energy, is the value for the cost of other energy sources π^e.

LDC	Gross revenue (million R$)	Natural gas purchase (million R$)	Net pro t (million R$)	Investment (million R$)	Natural gas volume (million m³)
Sulgas	896	601	80	26	717
SCGas	904	564	29	31	631
Compagas	777	467	62	36	467
Comgas	8614	3575	926	468	4917
Gas Brasiliano	498	273	50	21	273
Naturgy São Paulo	720	408	46	36	410
Naturgy Rio Capital	4568	2624	297	161	3255
Naturgy Rio Interior	2844	2223	89	45	2889
Gasmig	2187	1480	141	48	1261
MSGas	375	286	17	18	639
Bahiagas	2017	1368	128	41	1360
Copergas	1238	830	92	30	1554

Table 2.2: Relevant annual average operational and financial statistics for each LDC.

There is a complex regulatory framework in order to determine the tariffs LDCs will charge for clients from different sectors and for different levels of natural gas consumption. My approach here is to avoid these complexities and select LDCs parameters considering only some key average operational and financial statistics and the model equations related to them.

Under the assumption of steady state, distribution operates on full capacity (g_{ss} =

G_{ss}) and Equation 2.2 gives us $\pi^G = \frac{I^d_{ss}}{\delta^d g_{ss}}$. Therefore, I used each LDC's average investment for I^d_{ss} and average natural gas volume for g_{ss} to adjust π^G.

Let $\Pi^d_{ss} = \left(p^g_{ss} \quad \pi^g_{ss} \quad z^d\right) g_{ss}$ be the LDC's steady state profit. Solving Equations 2.4 and 2.5 in steady state for the elasticity of substitution between natural gas and capital ρ:

$$\rho = \frac{\frac{^{d}_{ss}}{g_{ss}} + \pi^g_{ss} + z^d}{\frac{^{d}_{ss}}{g_{ss}} \quad \pi^G \left(r_{ss} + \delta^d\right)} \tag{2.27}$$

Using the average net profit for Π^d_{ss} and the other adjusted parameters in Equation 2.27 gives us ρ.

LDC	Parameter				
	π^g	π^e	z^d	π^G	ρ
Sulgas	0.0011	0.0083	0.0004	0.000049	11.2
SCGas	0.0020	0.0092	0.0010	0.000110	33.5
Compagas	0.0014	0.0128	0.0006	0.000104	12.9
Comgas	0.0002	0.0012	0.0002	0.000031	9.3
Gas Brasiliano	0.0057	0.0209	0.0032	0.000443	9.9
Naturgy São Paulo	0.0039	0.0139	0.0022	0.000344	16.1
Naturgy Rio Capital	0.0012	0.0016	0.0007	0.000073	15.8
Naturgy Rio Interior	0.0018	0.0018	0.0004	0.000037	33.1
Gasmig	0.0012	0.0046	0.0004	0.000040	15.7
MSGas	0.0028	0.0091	0.0005	0.000170	23.1
Bahiagas	0.0021	0.0040	0.0008	0.000065	16.1
Copergas	0.0020	0.0035	0.0007	0.000070	13.5

Table 2.3: LDC specific directly adjusted parameters.

2.3.2 Calibration of parameters

Some parameters could not be adjusted directly from data or estimations from other studies. The approach adopted here was to jointly calibrate them in order to match some model moments with data. Let $\mathbf{\Theta} = (A^g, A^e, A, \alpha^g, \gamma, \psi)^{>}$ be the vector of parameters to be calibrated. Let $\mathbf{m}_d$ 2 R^6 be a vector of moments obtained from data, and let $\mathbf{m}(\mathbf{\Theta})$ be the model moments counterparts for $\mathbf{m}_d$. The optimal calibrated parameters vector, $\mathbf{\Theta}$, is

$$\mathbf{\Theta} \quad = \arg\min \left[\mathbf{m}(\mathbf{\Theta}) \quad \mathbf{m}_d\right]^{>} \mathbf{W} \left[\mathbf{m}(\mathbf{\Theta}) \quad \mathbf{m}_d\right] \tag{2.28}$$

Since all selected moments were positive, I minimized the sum of relative squared errors, meaning the weight matrix used was $\mathbf{W} = \text{diag}\left(1/\mathbf{m}^2_{d,i}\right)^6_{i=1}$.

The moments selected as targets for the calibration are the following:

1. Average price of natural gas, equal to the ratio between gross income and natural gas volume, given by p^g_{ss} in the model;
2. Share of natural gas energy in total energy consumption, equal to 0.131, given by $\frac{g_{ss}}{g_{ss}+e_{ss}}$ in the model;
3. Regional GDP, given by y_{ss} in the model;
4. Ratio between capital income and the sum of capital income and energy income, equal to 0.896, given by $\frac{r^g_{ss}k^g_{ss}+r^e_{ss}k^e_{ss}}{q^g_{ss}s^g_{ss}+q^e_{ss}s^e_{ss}}$ in the model;
5. Natural gas efficiency relative to other energy sources, equal to 1.27, given by $\frac{s^g_{ss}/g_{ss}}{s^e_{ss}/e_{ss}}$ in the model;
6. Total labor, given by n_{ss} in the model;

Regional GDP was taken from the regional accounts published by the Brazilian statistics office (IBGE), reporting GDP for each state. I used the average value between 2014-2018.[8] Most LDCs in this study are the only ones in their state, so state GDP is used. But the states of São Paulo and Rio de Janeiro have multiple companies. In those cases, I split the state GDP among companies proportional to their revenue. To prevent calibrated parameters from having a large range of magnitude, I divided all monetary values by the GDP, and set the GDP target to 1. The natural gas efficiency relative to other energy sources was taken from the Energy Information System of the Ministry of Mines and Energy (SIE Brasil - MME). The most recent values were from 2004. Efficiency here is in the physical sense, that is, the share of energy that is transformed into effective work. Labor was set to 44/168, the average working week time. Table 2.5 contains the values for each target.

Table 2.4 shows the calibrated values for each parameter and each company. Most values are relatively stable across the companies, except for the productivity parameters A^g and A^e, which present larger heterogeneity. Values for the elasticity of substitution between capital services powered by different energy sources, γ, are close to 1, an expected outcome since capital service from both energy sources are close substitutes.[9]. Table 2.6 summarizes the calibration errors. Most of the deviations are very small, with the price of natural gas being the one with larger deviations, but never beyond 6%.

[8] Values for 2019 were not available at the time of this study

[9] The limit case of γ = 1 in Equation 2.12 is of perfect substitutes.

LDC	Parameter					
	A^g	A^e	A	α^g	γ	ψ
Sulgas	118	126	0.206	0.984	0.994	541
SCGas	734	795	0.101	0.970	0.986	539
Compagas	96	107	0.224	0.979	0.995	537
Comgas	162	144	0.180	0.993	0.990	538
Gas Brasiliano	203	222	0.171	0.917	0.992	537
Naturgy São Paulo	1784	1945	0.072	0.940	0.988	538
Naturgy Rio Capital	34	32	0.329	0.978	0.970	539
Naturgy Rio Interior	47	45	0.289	0.976	0.964	540
Gasmig	94	95	0.225	0.982	0.993	539
MSGas	155	165	0.186	0.966	0.995	538
Bahiagas	7805	9489	0.037	0.969	0.864	539
Copergas	16	16	0.444	0.970	0.979	539

Table 2.4: Calibrated parameters.

LDC	Targets for each moment					
	Price NG	NG energy share	GDP	Capital income	NG relative efficiency	Total labor
Sulgas	0.00171					
SCGas	0.00321					
Compagas	0.00227					
Comgas	0.00057					
Gas Brasiliano	0.01034					
Naturgy São Paulo	0.00688					
Naturgy Rio Capital	0.00206	0.131	1	0.896	1.266	0.262
Naturgy Rio Interior	0.00232					
Gasmig	0.00180					
MSGas	0.00362					
Bahiagas	0.00316					
Copergas	0.00292					

Table 2.5: Calibration targets for each moment.

2.4 Experiments

With the model reasonably calibrated to real world data, I performed some counterfactual exercises in order to investigate how an increase in the competition within the natural gas production sector would affect LDCs and regional economies. This is done by changing the value of the natural gas price π_t^g. For each LDC, I consider two scenarios: one where only the natural gas price changes; and another where both energy sources prices change (π_t^g and π_t^e). I ran the model for 100 periods, which was enough for the model to move from one steady state to another.

LDC	Model relative deviation from data moments (%)					
	Price NG	NG share	GDP	Capital income	NG rel. e .	Labor
Sulgas	-2.9	-0.024	0.012	1.585	-0.026	-0.059
SCGas	-3.4	-0.019	-0.005	1.409	-0.025	0.024
Compagas	-4.6	-0.025	-0.016	1.628	-0.027	0.079
Comgas	-5.4	-0.014	-0.011	1.204	-0.023	0.055
Gas Brasiliano	-4.3	-0.013	-0.015	1.190	-0.020	0.074
Naturgy São Paulo	-5.0	-0.014	-0.007	1.206	-0.021	0.037
Naturgy Rio Capital	-3.5	0.000	0.000	0.097	-0.003	-0.000
Naturgy Rio Interior	-1.6	0.000	0.001	0.081	-0.003	-0.004
Gasmig	-2.2	-0.017	-0.006	1.318	-0.023	0.032
MSGas	-4.7	-0.016	-0.008	1.317	-0.023	0.039
Bahiagas	-2.0	-0.012	-0.004	1.157	-0.024	0.021
Copergas	-2.4	-0.005	-0.001	0.734	-0.014	0.004

Table 2.6: Calibration relative deviation for each moment.

2.4.1 Decrease in the price of natural gas

In order to simulate an increase in competition in the production of natural gas, I assume a permanent reduction of 5% in the price of natural gas bought by the LDCs.[10] The model starts at steady state in period zero, and become aware of future changes in price in the next period, with no unforeseen shocks afterwards. All other parameters were kept constant, in particular the price of other energy sources.

A important transition pattern can be seen in the figures of Appendix 2.B and dictates the behavior of all transitions is the composition of two dynamics with different speeds. First, a quick transition taking only a few years that is driven by the expansion of pipelines. Second, a slow transition driven by changes in both capital stocks, taking many decades to approach steady state.

Short and long run impacts over different LDCs are shown in Table 2.7. Long run tariff reduction ranged between 2.5% and 4.2%, all below the 5% reduction of natural gas price. The reason for this can be understood by inspecting Equation 2.4. The change in pipeline capacity price π_t^d is hampered by the distribution costs parameter z^d and investment shadow cost λ_t, as both of which remained constant.[11]

Beside tariffs, long run companies' activities increased significantly. Volumes of natural gas sold, revenues and profits all increased by similar magnitudes, although differently for each company. Companies like SCGás, Naturgy Rio Capital, Naturgy Rio Interior and MSGás all had increases beyond 100%, while Comgás, the largest company evaluated

[10] Currently, Petrobras has an average pro t margin of around 10% in its natural gas operation. Assuming a reduction of this margin by half, keeping costs constant, this implies a price reduction of 5%

[11] In steady state, $\lambda_{ss} = \pi^G \left(r_{ss} + \delta^d\right)$.

in this study, had a smaller but still significant increase of about 34%. This can be in part attributed to the smaller profit margin of this company, reflected in a smaller value for the elasticity of substitution ρ, as can be seen in Table 2.3.

Most of the changes happened in the first year after the shock, as can be seen in the short run changes in Table 2.7. Plots of the transitions for these variables over the years, for each LDC, can be found in the Appendix.

LDC	Short run % changes				Long run % changes			
	Tari	Volume	Revenue	Pro t	Tari	Volume	Revenue	Pro t
Sulgas	-3.3	47	42	49	-3.8	71	65	65
SCGas	-2.2	105	100	168	-3.3	224	213	215
Compagas	-2.7	43	39	50	-3.4	71	65	65
Comgas	-2.0	22	19	23	-2.5	36	33	33
Gas Brasiliano	-2.7	32	29	34	-3.2	57	52	53
Naturgy São Paulo	-2.4	48	44	61	-3.2	83	77	77
Naturgy Rio Capital	-2.6	49	45	58	-3.2	75	69	70
Naturgy Rio Interior	-3.4	144	135	189	-4.1	269	254	254
Gasmig	-3.2	68	62	74	-3.7	113	105	106
MSGas	-2.8	95	90	142	-4.2	263	248	249
Bahiagas	-3.2	61	56	66	-3.7	79	72	72
Copergas	-3.3	57	52	60	-3.7	80	73	74

Table 2.7: Impact of a 5% natural gas cost reduction over LDC results.

The impact upon each regional economy natural gas participation on energy consumption, which was initially 13.1% for all regional economies (see Table 2.5) rose substantially in most cases. Table 2.8 shows both the short and long run participation of natural gas, considering short term to be the very next year after the occurrence of the price shock. A significant part of the increase in participation occurs in the short run, meaning that there is a quick expansion in the distribution capacity. The rest of the expansion, though, occurs in a much slower pace, taking decades to reach steady state. This is because capital producers take a much longer time to substitute other energy sources powered capital to natural gas powered capital.

Now considering the effects upon the local economy, shown in Table 2.9, there is some positive impact over GDP in the short run, with median 0.1% within regions and a maximum of 0.58% for Naturgy Rio Interior. However, this impact is smaller in the long run, with median 0.02%, since there is only a quick surge in investment in new pipelines in the short run that does not last long. As for capital stocks, changes are more prominent in the long run and quite diverse among regions. For instance, even though most regions display an increase in natural gas powered capital, we can see a decrease

LDC	NG energy share (%)		
	Current	Short run (after 1 year)	Long run
Sulgas	13.1	18.2	20.9
SCGas	13.1	23.7	33.3
Compagas	13.1	17.7	20.8
Comgas	13.1	15.5	17.3
Gas Brasiliano	13.1	16.7	19.7
Naturgy São Paulo	13.1	18.3	22.0
Naturgy Rio Capital	13.1	18.5	21.2
Naturgy Rio Interior	13.1	27.2	36.6
Gasmig	13.1	20.2	25.1
MSGas	13.1	22.9	37.3
Bahiagas	13.1	19.6	21.3
Copergas	13.1	19.2	21.8

Table 2.8: Impact of a 5% natural gas cost reduction over energy share.

for Naturgy Rio Interior and Bahiagás. In order to understand this ambiguous direction of change, we must analyse two effects in play. First, as natural gas became cheaper relative to capital rental, the natural gas powered capital service company substitute capital for gas as inputs, driving down the capital amount. Second, the demand for this capital service increases, since it becomes cheaper. The magnitude of the second effect is stronger as γ approaches 1, becoming closer substitutes, and it can be seen in Table 2.4 that the calibrated values for Naturgy Rio Interior and Bahiagás are smaller than for other companies, explaining why the first effect is dominant.

LDC	Short run % changes			Long run % changes		
	GDP	Capital (NG)	Capital (OS)	GDP	Capital (NG)	Capital (OS)
Sulgas	0.03	0.28	-0.10	0.01	10.79	-2.24
SCGas	0.10	0.05	-0.28	0.02	4.49	-1.95
Compagas	0.03	0.22	-0.08	0.01	9.27	-1.92
Comgas	0.04	0.30	-0.11	0.01	8.02	-1.72
Gas Brasiliano	0.06	0.46	-0.16	0.02	14.08	-2.99
Naturgy São Paulo	0.07	0.31	-0.19	0.02	8.61	-2.15
Naturgy Rio Capital	0.21	0.20	-0.39	0.06	5.03	-2.22
Naturgy Rio Interior	0.58	-1.23	-0.99	0.11	-7.65	-3.60
Gasmig	0.09	0.48	-0.23	0.02	17.97	-3.97
MSGas	0.10	0.69	-0.39	0.03	34.88	-7.95
Bahiagas	0.16	-0.47	-0.13	0.04	-2.42	-0.27
Copergas	0.16	0.39	-0.31	0.04	8.03	-2.37

Table 2.9: Impact of a 5% natural gas cost reduction over regional economy.

2.4.2 Decrease in all energy prices keeping energy shares constant

One of the main conclusions from the previous experiment is that natural gas consumption is very elastic to changes in price. Just a small reduction of 5% in price caused long run volume changes up to beyond 200%. Even in the short run changes were very high. The main reason for this is the high substitutability between the different capital services, which is not just something captured by the calibrated parameter γ being close to unity, but also realistic fact since capital services are expected to be similar, regardless of the energy source that powers it.

As prices for both energy sources are exogenous in the model, and it is realistic to expect that prices for other energies would drop as well as a response for the drop in natural gas price due to competition between energy sources, I performed another experiment were, in fact, both prices drop.[12] However, in order to discipline this change, I kept the 5% drop in natural gas price, but the drop in other energies price is only enough to keep energy participation constant in the long run. Table 2.10 summarizes the price reduction for each regional economy.

LDC	% drop in OS price
Sulgas	2.90
SCGas	13.15
Compagas	2.58
Comgas	2.84
Gas Brasiliano	3.47
Naturgy Sao Paulo	6.32
Naturgy Rio Capital	12.34
Naturgy Rio Interior	29.96
Gasmig	4.77
MSGas	6.12
Bahiagas	29.56
Copergas	10.09

Table 2.10: Other energy sources price drop required to keep long run energy shares constant.

Table 2.11 displays the short and long run impact over the companies. Long run changes in tariffs are the same as in the first experiment, since their long run values do not depend on other energies price π^e_{ss}, as can be seen by close inspection of Equations 2.4 and 2.5. As for long run volumes, revenues and profits, increases were much smaller

[12] Huntington (2007) states that natural gas prices tend to follow oil prices, and Mathias and Szklo (2007) also points out the competition between natural gas and water within the electric power industry.

now, although still significant. Long run increases in volume, for instance, go from 6.2% for Comgás up to 61.4% for Naturgy Rio Interior. However, short run changes are still large in this experiment, since the LDC can take advantage of increased demand due to a lower tariff as the capital composition change towards other energy sources takes much longer to occur.

LDC	Short run % changes				Long run % changes			
	Tari	Volume	Revenue	Pro t	Tari	Volume	Revenue	Pro t
Sulgas	-3.4	43	38	44	-3.8	9	5	5
SCGas	-2.6	72	68	105	-3.3	29	25	25
Compagas	-2.8	40	36	46	-3.4	9	5	5
Comgas	-2.1	19	17	20	-2.5	6	4	4
Gas Brasiliano	-2.8	29	25	30	-3.2	8	5	5
Naturgy São Paulo	-2.5	40	36	49	-3.2	14	10	10
Naturgy Rio Capital	-2.8	34	31	38	-3.2	21	17	17
Naturgy Rio Interior	-3.8	60	54	69	-4.1	61	55	55
Gasmig	-3.3	59	53	63	-3.7	13	9	9
MSGas	-3.0	81	75	118	-4.2	18	13	14
Bahiagas	-3.5	35	30	35	-3.7	51	46	46
Copergas	-3.4	43	38	44	-3.7	18	14	14

Table 2.11: Impact of energy prices reduction, keeping long run energy shares constant, over LDC results.

Since the price of other energies now drop as well, and they have a larger participation, the impact in the regional economy is now more significant. Increases in GDP now went as high as 2.7% for Naturgy Rio Interior in the long run, as shown in Table 2.12. Even the short run increase in GDP in more pronounced than before, although below long run values. This is because the drop of other energy sources price have a quick effect over the production sector which impacts GDP more than the quick surge in investment due to distribution grid expansion. As for capital, we see a large drop in natural gas powered capital stock for all regional economies. This is because the parameter ρ that determines the monopolist mark-up of the LDC is also the elasticity of substitution between fuel and capital in the energy service production function.

2.4.3 Uniform decrease in all energy prices

In a third counterfactual, instead of keeping long term energy shares constant, I now assume that all energy prices fall uniformly by 5%. Overall, short term responses were not so different from the previous experiment, since the dominant effect in the first periods is the natural gas price reduction. On the other hand, long run responses are quite different,

LDC	Short run % changes			Long run % changes		
	GDP	Capital (NG)	Capital (OS)	GDP	Capital (NG)	Capital (OS)
Sulgas	0.18	-0.97	0.23	0.22	-29.41	5.83
SCGas	0.80	-3.84	0.97	1.06	-58.36	12.24
Compagas	0.16	-0.93	0.22	0.19	-30.38	5.99
Comgas	0.18	-0.70	0.17	0.22	-15.76	3.18
Gas Brasiliano	0.23	-0.88	0.20	0.27	-21.65	4.32
Naturgy São Paulo	0.40	-1.74	0.41	0.49	-32.32	6.57
Naturgy Rio Capital	0.84	-2.45	0.62	0.99	-27.47	5.82
Naturgy Rio Interior	2.11	-6.50	1.80	2.71	-59.58	13.03
Gasmig	0.33	-1.47	0.30	0.37	-37.60	7.43
MSGas	0.42	-2.09	0.37	0.49	-56.06	10.97
Bahiagas	1.84	-2.84	1.51	2.46	-17.39	6.46
Copergas	0.68	-2.17	0.55	0.80	-29.17	6.18

Table 2.12: Impact of energy prices reduction, keeping long run energy shares constant, over regional economy.

LDC	Short run % changes				Long run % changes			
	Tari	Volume	Revenue	Pro t	Tari	Volume	Revenue	Pro t
Sulgas	-3.4	40	35	41	-3.8	-23	-26	-26
SCGas	-2.4	95	90	144	-3.3	135	127	128
Compagas	-2.8	36	32	42	-3.4	-31	-34	-34
Comgas	-2.1	17	15	18	-2.5	-13	-15	-15
Gas Brasiliano	-2.8	27	23	28	-3.2	-10	-12	-12
Naturgy São Paulo	-2.5	41	38	51	-3.2	26	22	23
Naturgy Rio Capital	-2.7	43	40	50	-3.2	52	47	47
Naturgy Rio Interior	-3.5	131	123	168	-4.1	230	216	217
Gasmig	-3.3	58	53	63	-3.7	9	5	5
MSGas	-3.0	83	78	122	-4.2	48	42	43
Bahiagas	-3.3	57	52	61	-3.7	74	68	68
Copergas	-3.3	50	45	52	-3.7	48	42	42

Table 2.13: Impact of uniform energy prices reduction over LDC results.

especially for the LDC results, as can be seen in Table 2.13. While most LDCs still present increases in volume, revenue and profit, the companies Sulgás, Compagás, Comgás and Gás Brasiliano display decreases in these values. This is because the threshold of other energy sources price drop necessary for a fall in natural gas energy share are smaller, as can be seen in Table 2.10. These companies show a greater sensitivity to price changes in other energy sources. This in also clear when looking at the natural gas energy share changes in Table 2.14.

Since the energy prices change was now uniform, changes in GDP were more similar across regions in both short and long run, as seen in Table 2.15. There was still a decrease in natural gas powered capital stock, more pronounced in the long run, and an increase

LDC	NG energy share (%)		
	Current	Short run (after 1 year)	Long run
Sulgas	13.1	16.6	9.1
SCGas	13.1	21.8	24.4
Compagas	13.1	16.3	8.1
Comgas	13.1	14.3	10.5
Gas Brasiliano	13.1	15.3	10.8
Naturgy Sao Paulo	13.1	16.8	14.7
Naturgy Rio Capital	13.1	17.1	17.7
Naturgy Rio Interior	13.1	25.1	32.2
Gasmig	13.1	18.4	12.7
MSGas	13.1	20.7	16.3
Bahiagas	13.1	18.4	19.9
Copergas	13.1	17.7	17.2

Table 2.14: Impact of uniform energy prices reduction over energy share.

in other energy sources powered capital stock, with the exception of Naturgy Rio Interior where both there was a very small decrease.

LDC	Short run % changes			Long run % changes		
	GDP	Capital (NG)	Capital (OS)	GDP	Capital (NG)	Capital (OS)
Sulgas	0.29	-1.83	0.45	0.38	-50.44	10.11
SCGas	0.36	-1.45	0.20	0.38	-24.20	4.39
Compagas	0.28	-1.95	0.48	0.39	-56.14	11.22
Comgas	0.30	-1.45	0.38	0.38	-31.12	6.38
Gas Brasiliano	0.31	-1.45	0.36	0.39	-34.46	6.97
Naturgy Sao Paulo	0.33	-1.32	0.29	0.38	-24.88	4.96
Naturgy Rio Capital	0.46	-0.86	0.01	0.41	-8.79	1.15
Naturgy Rio Interior	0.80	-2.03	-0.55	0.46	-17.41	-0.64
Gasmig	0.35	-1.57	0.33	0.39	-39.65	7.85
MSGas	0.36	-1.61	0.24	0.40	-44.97	8.61
Bahiagas	0.41	-0.82	0.11	0.38	-4.73	0.73
Copergas	0.41	-0.88	0.11	0.40	-11.52	2.08

Table 2.15: Impact of uniform energy prices reduction over regional economy.

2.5 Concluding Remarks

In this paper I developed a structural dynamic model with energy inputs and monopolistic natural gas distribution company. This model was adjusted to 12 of the main Brazilian LDCs and the regional economies they serve. The model was built in order to assess the impact of increased competition in the production of natural gas, represented by a decrease in natural gas price.

I found out that increases in natural gas consumption are very significant in both short and long run, as long as the natural gas price goes down relative to the price of other energy sources. Otherwise, the short run increases do not hold in the long run. I also found out that changes in natural gas demand are much slower, since the substitution of capital that uses a certain energy source for another takes a long time. A possible extension for the proposed framework is to expand the energy production sector within the model in order to capture the competition between sources.

Bibliography

[1] Sami Alpanda and Adrian Peralta-Alva. "Oil crisis, energy-saving technological change and the stock market crash of 1973–74". Review of Economic Dynamics 13.4 (2010), pp. 824–842.

[2] Göran Bergendahl. "Efficient strategies for natural gas expansion under uncertainty: The case of Sweden". Energy economics 10.2 (1988), pp. 100–106.

[3] Paul J Burke and Hewen Yang. "The price and income elasticities of natural gas demand: International evidence". Energy Economics 59 (2016), pp. 466–474.

[4] Benjamin S Cheng. "Energy consumption and economic growth in Brazil, Mexico and Venezuela: a time series analysis". Applied Economics Letters 4.11 (1997), pp. 671–674.

[5] Leila Dagher. "Natural gas demand at the utility level: an application of dynamic elasticities". Energy Economics 34.4 (2012), pp. 961–969.

[6] Empresa de Pesquisa Energéticas EPE. "Balanço Energético Nacional 2020-Ano base 2019". Rio de Janeiro (2020).

[7] Bradley T Ewing, Farooq Malik, and Ozkan Ozfidan. "Volatility transmission in the oil and natural gas markets". Energy Economics 24.6 (2002), pp. 525–538.

[8] Hillard G Huntington. "Industrial natural gas consumption in the United States: An empirical model for evaluating future trends". Energy Economics 29.4 (2007), pp. 743–759.

[9] Melissa Cristina Mathias and Alexandre Szklo. "Lessons learned from Brazilian natural gas industry reform". Energy Policy 35.12 (2007), pp. 6478–6490.

[10] Guilherme V Moura. "Multiplicadores fiscais e investimento em infraestrutura". Revista Brasileira de Economia 69.1 (2015), pp. 75–104.

[11] Rodrigo M Pereira. "Investment and uncertainty in a quadratic adjustment cost model: Evidence from Brazil". Revista Brasileira de Economia 55.2 (2001), pp. 283–311.

[12] Alexander Cotte Poveda and Clara Inés Pardo Martínez. "Trends in economic growth, poverty and energy in Colombia: long-run and short-run effects". Energy Systems 2.3 (2011), pp. 281–298.

[13] Hadi Sasana. "The impact of fossil and renewable energy consumption on the economic growth in Brazil, Russia, India, China and South Africa" (2017).

[14] José Ronaldo de Castro Souza Júnior and Felipe Moraes Cornelio. "Estoque de capital fixo no Brasil: séries desagregadas anuais, trimestrais e mensais" (2020).

[15] David I Stern. "The role of energy in economic growth". International energy and poverty (2015), pp. 35–47.

[16] Zhang Zhixin and Ren Xin. "Causal relationships between energy consumption and economic growth". Energy Procedia 5 (2011), pp. 2065–2071.

2.A Algorithm for finding the equilibrium

- Calculate the equilibrium objects that will not be updated during the iterations:

$$p_t^e = \pi^e \tag{2.29}$$

$$\Lambda_t = \frac{1}{1 + r_t} \tag{2.30}$$

$$\varepsilon = \rho \tag{2.31}$$

- Guess G_t, $k_t^{g,S}$, $k_t^{e,S}$;
- Update the equilibrium prices:

$$\lambda_t = \Pi^d \left\{ \frac{1}{\Lambda_t} \left[1 + \phi^d \left(\frac{G_t}{G_{t-1}} - 1 \right) \right] - \frac{\phi^d}{2} \left[\left(\frac{G_{t+1}}{G_t} \right)^2 - 1 \right] - \left(1 - \delta^d \right) \right\} \tag{2.32}$$

$$r_t^g = \frac{1}{\Lambda_t}\left[1+\phi^g\left(\frac{k_t^{g,S}}{k_{t-1}^{g,S}}-1\right)\right]-\frac{\phi^g}{2}\left[\left(\frac{k_{t+1}^{g,S}}{k_t^{g,S}}\right)^2-1\right]-\left(1-\delta^g\right) \tag{2.33}$$

$$r_t^e = \frac{1}{\Lambda_t}\left[1+\phi^e\left(\frac{k_t^{e,S}}{k_{t-1}^{e,S}}-1\right)\right]-\frac{\phi^e}{2}\left[\left(\frac{k_{t+1}^{e,S}}{k_t^{e,S}}\right)^2-1\right]-\left(1-\delta^e\right) \tag{2.34}$$

$$p_t^g = \frac{\varepsilon}{\varepsilon-1}\left(\pi_t^g+z^d+\lambda_t\right) \tag{2.35}$$

$$q_t^g = \frac{1}{A^g}\left[\left(\alpha^g\right)^\rho\left(r_t^g\right)^{1-\rho}+\left(1-\alpha^g\right)^\rho\left(p_t^g\right)^{1-\rho}\right]^{\frac{1}{1-\rho}} \tag{2.36}$$

$$q_t^e = \frac{1}{A^e}\left(\frac{r_t^e}{\alpha^e}\right)^{\alpha^e}\left(\frac{p_t^e}{1-\alpha^e}\right)^{1-\alpha^e} \tag{2.37}$$

$$w_t = (1-\alpha)\left\{A\left[\frac{\alpha}{2\left(q_t^g q_t^e\right)^{\frac{1}{2}}}\right]^\alpha\right\}^{\frac{1}{1-\alpha}} \tag{2.38}$$

$$q_t = \alpha\left[A\left(\frac{1-\alpha}{w_t}\right)^{1-\alpha}\right]^{\frac{1}{\alpha}} \tag{2.39}$$

- Update the aggregate energy service:

$$s_t = \left(\frac{w_t}{A(1-\alpha)}\right)^{\frac{1}{\alpha}}\left(\frac{w_t}{\psi}\right)^{\frac{1}{\theta}} \tag{2.40}$$

- Update the energy service for each energy source:

$$s_t^g = \left(\frac{q_t}{q_t^g}\right)^{\frac{1}{1-\gamma}} s_t \tag{2.41}$$

$$s_t^e = \left(\frac{q_t}{q_t^e}\right)^{\frac{1}{1-\gamma}} s_t \tag{2.42}$$

- Update the equipment demand for each energy source:

$$k_t^{g,D} = \frac{1}{A^g}\left(\alpha^g A^g\frac{q_t^g}{r_t^g}\right)^\rho s_t^g \tag{2.43}$$

$$k_t^{e,D} = \alpha^e \frac{q_t^e}{r_t^e} s_t^e \tag{2.44}$$

- Update the quantity of natural gas

$$g_t = \left((1 - \alpha^g) A^g \frac{q_t^g}{p_t^g} \right)^{\rho} \frac{s_t^g}{A^g} \tag{2.45}$$

- Update G_t, $k_t^{g,S}$, $k_t^{e,S}$ aiming to make capital supply and demand match and the capacity constraint of the LDC. In the case of G_t, check if the capacity constraint is violated, moving λ_t towards 0 if that is the case;
- Once the values for G_t, $k_t^{g,S}$, $k_t^{e,S}$ are numerically found, update the remaining equilibrium objects:

$$I_t^d = G_{t+1} - \left(1 - \delta^d\right) G_t \tag{2.46}$$

$$I_t^g = k_{t+1}^{g,S} - \left(1 - \delta^d\right) k_t^{g,S} \tag{2.47}$$

$$I_t^e = k_{t+1}^{e,S} - (1 - \delta^e)\, k_t^{e,S} \tag{2.48}$$

$$e_t = (1 - \alpha^e) \frac{q_t^e}{p_t^e} s_t^e \tag{2.49}$$

$$n_t = \left(\frac{w_t}{\psi} \right)^{\frac{1}{\theta}} \tag{2.50}$$

$$c_t = w_t n_t \tag{2.51}$$

$$q_t = \alpha \left[A \left(\frac{1 - \alpha}{w_t} \right)^{1 - \alpha} \right]^{\frac{1}{\alpha}} \tag{2.52}$$

$$y_t = \frac{w_t n_t}{1 - \alpha} \tag{2.53}$$

2.B Transitions for each LDC

2.B.1 Sulgás

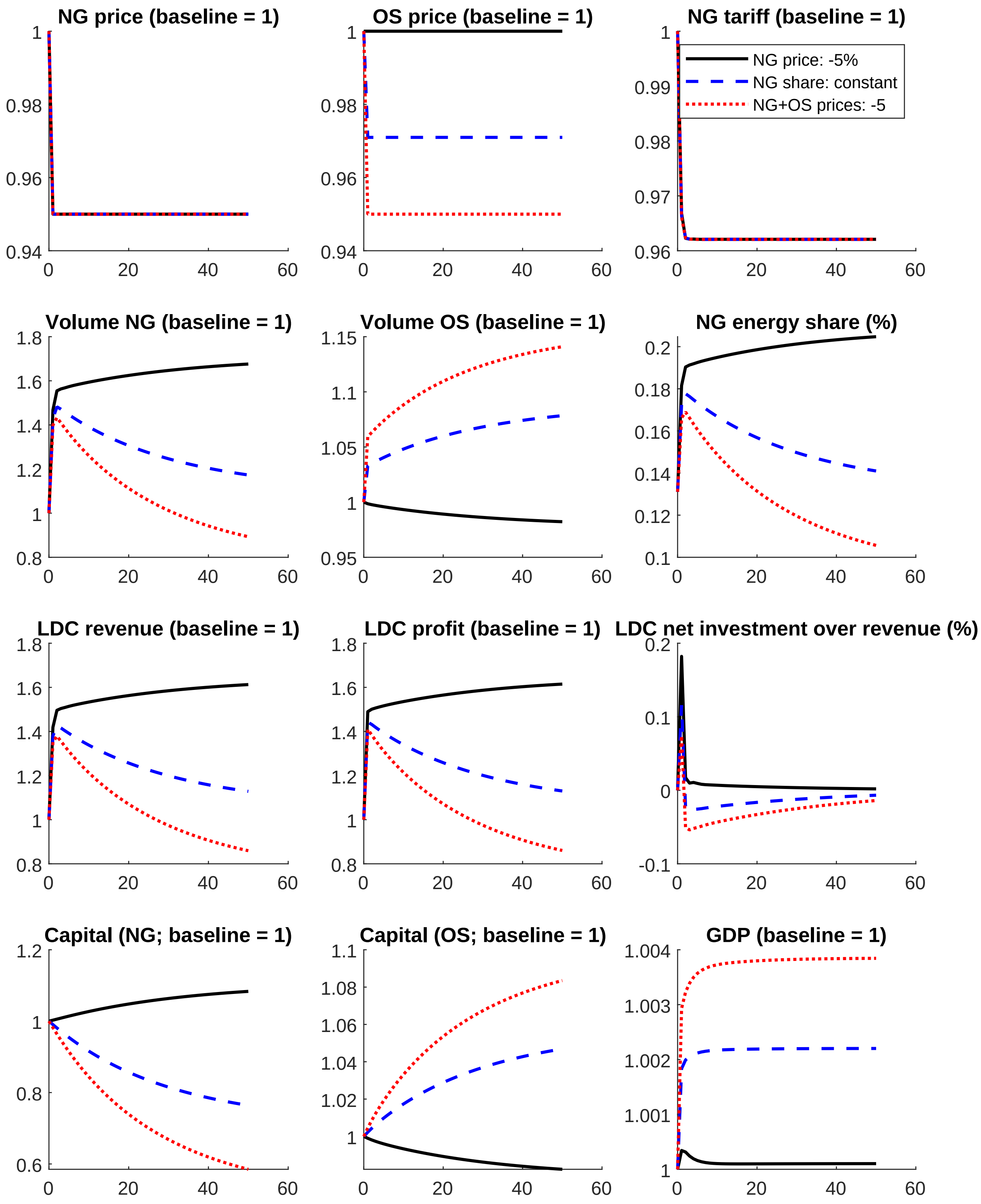

Figure 2.2: Transitions for Sulgás

2.B.2 SCGás

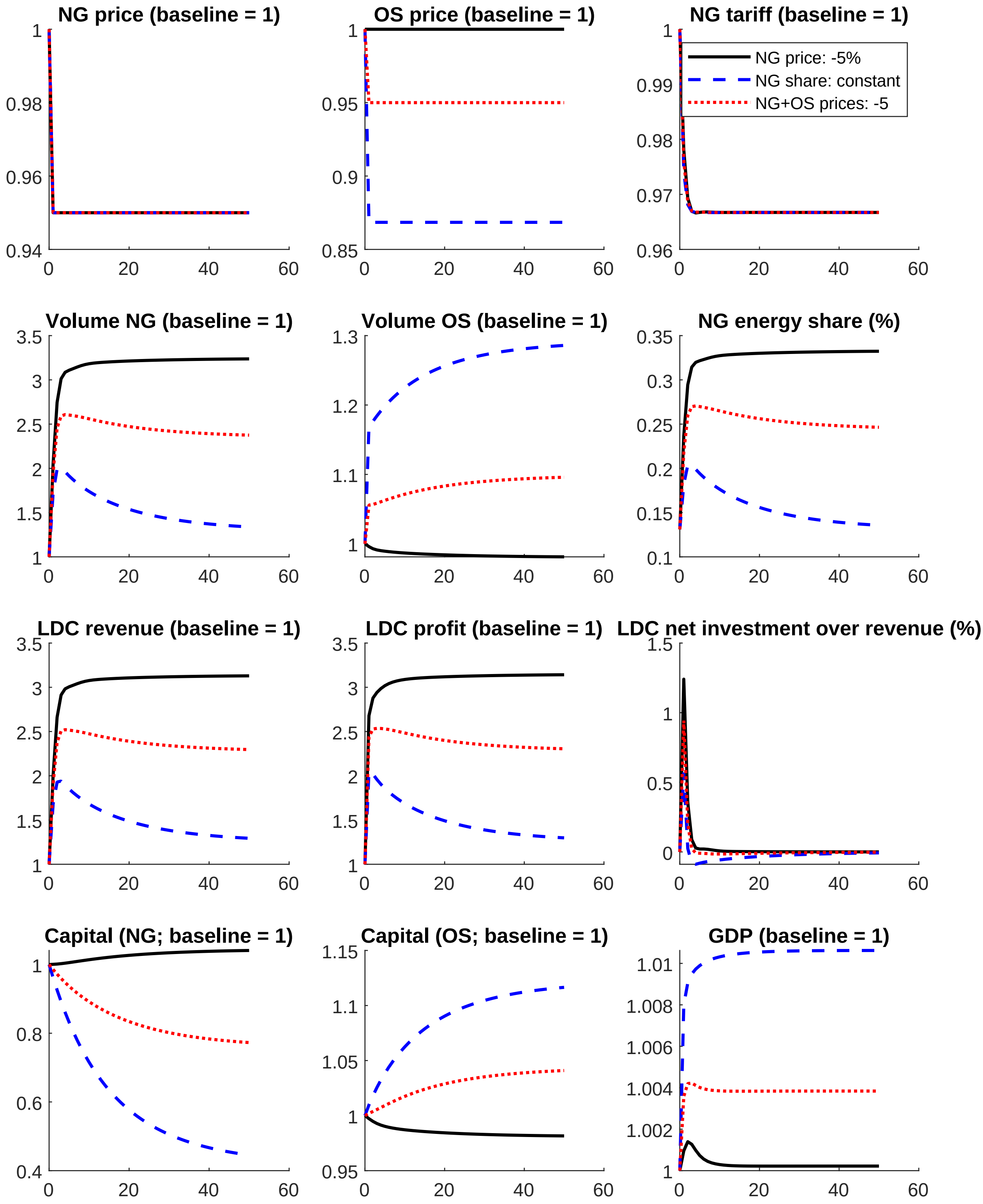

Figure 2.3: Transitions for SCGás

2.B.3 Compagás

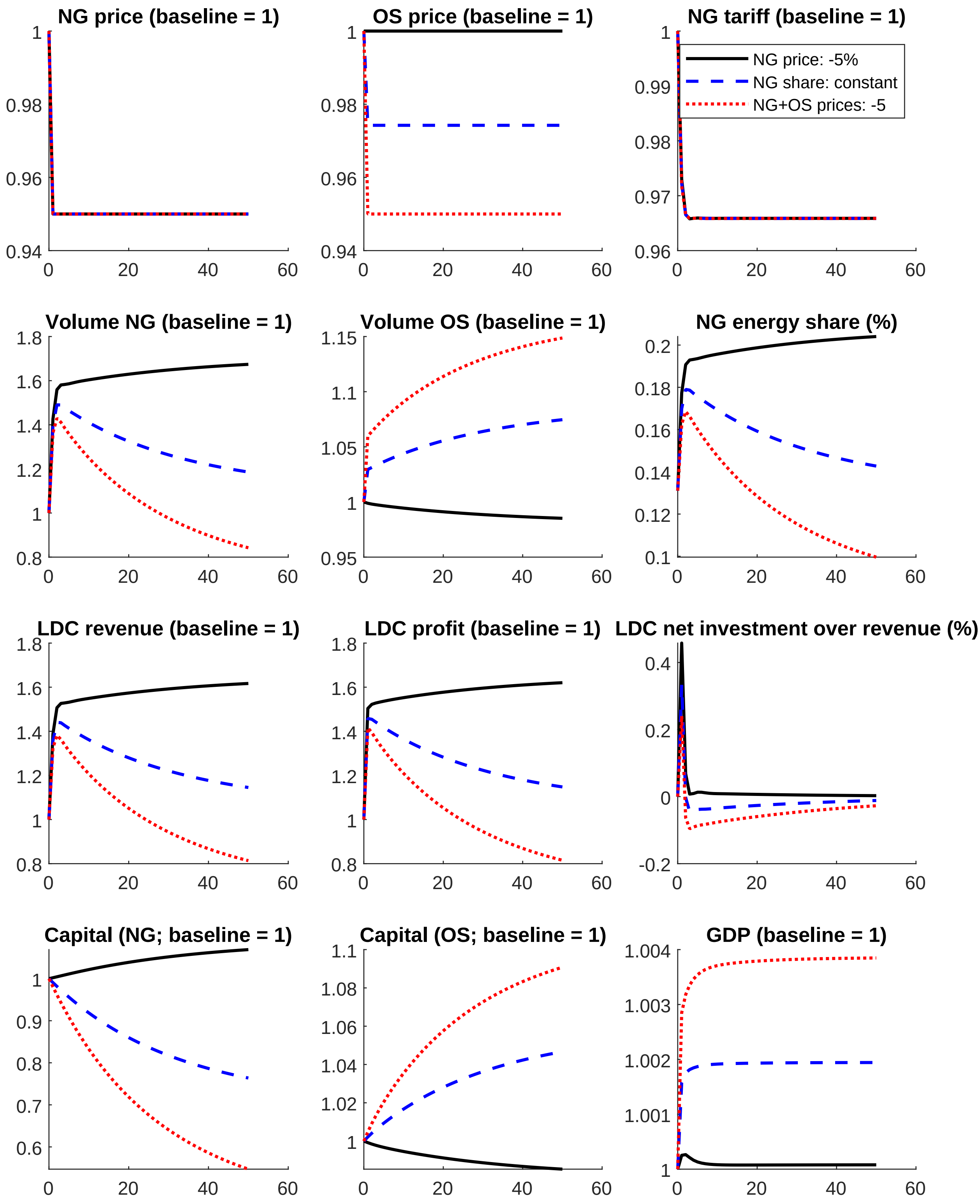

Figure 2.4: Transitions for Compagás

2.B.4 Comgás

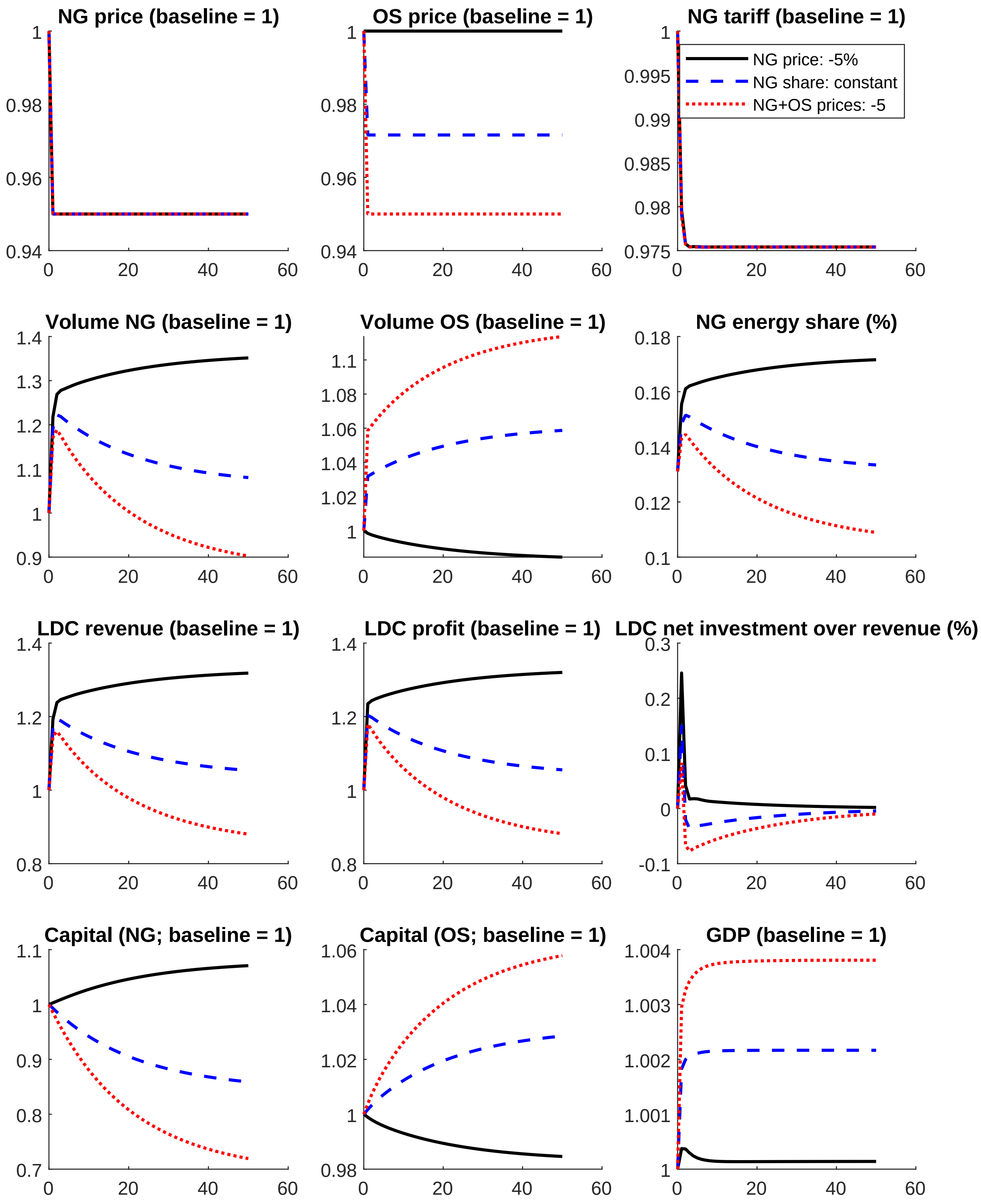

Figure 2.5: Transitions for Comgás

2.B.5 Gás Brasiliano

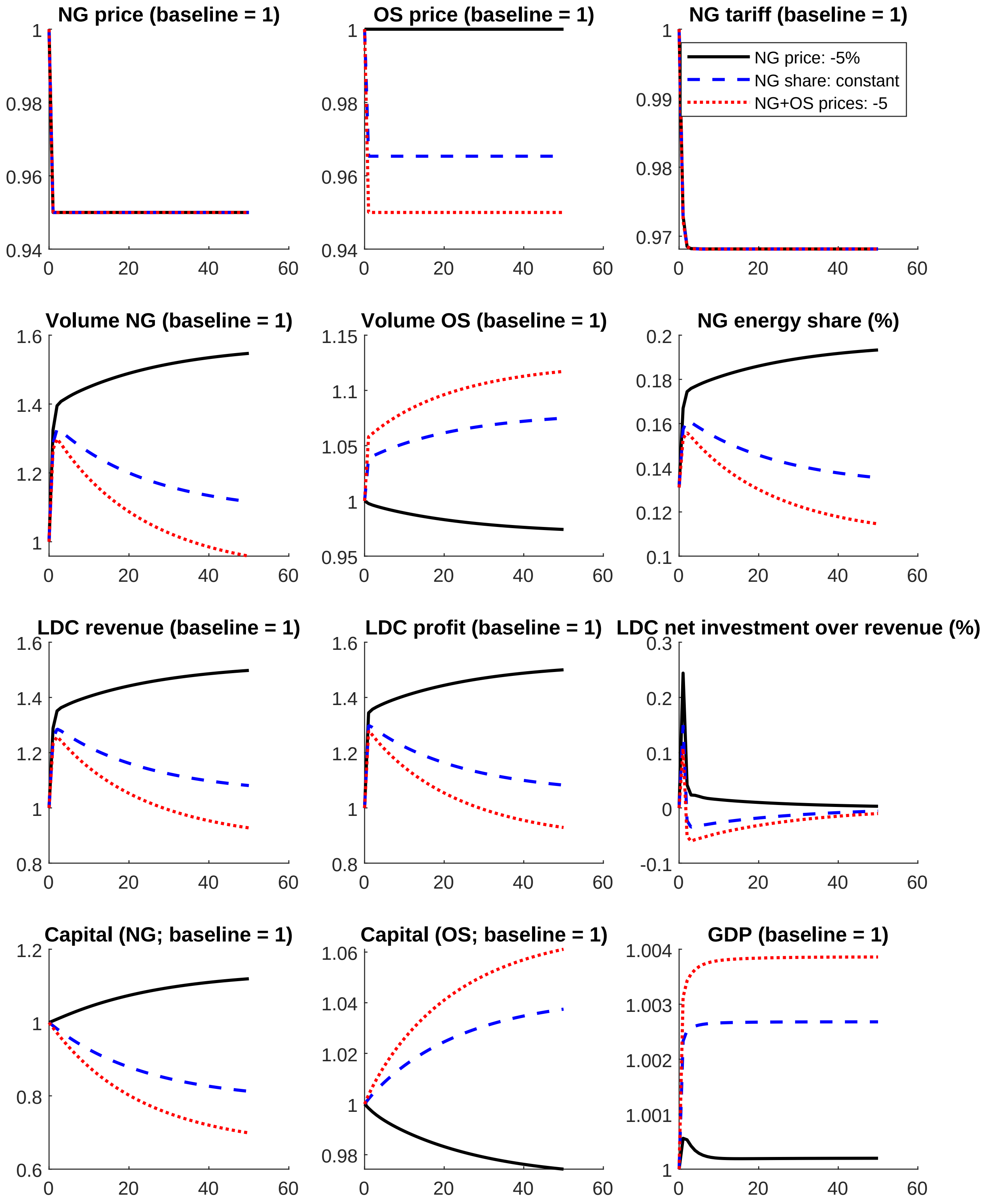

Figure 2.6: Transitions for Gás Brasiliano

2.B.6 Naturgy São Paulo

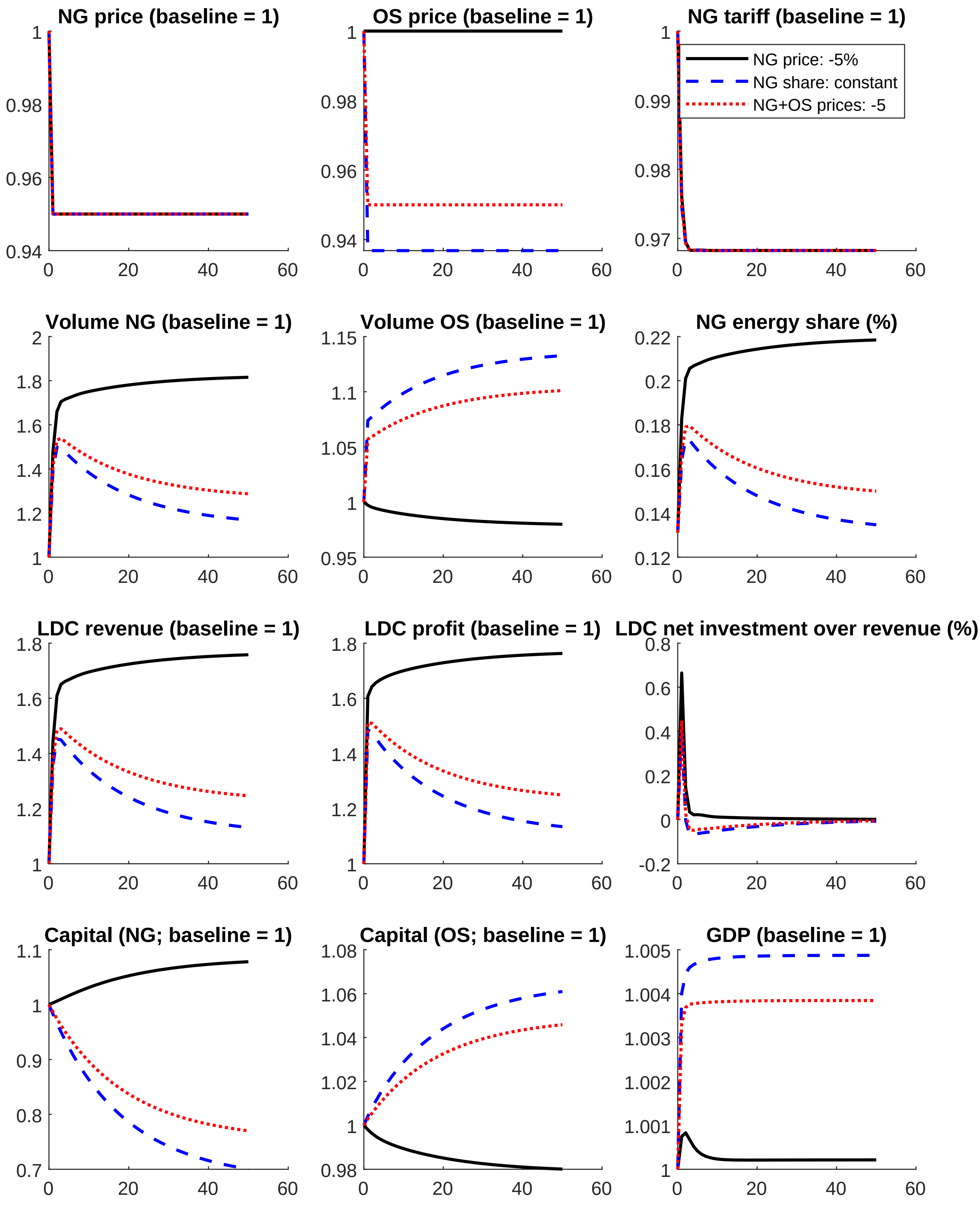

Figure 2.7: Transitions for Naturgy São Paulo

2.B.7 Naturgy Rio Capital

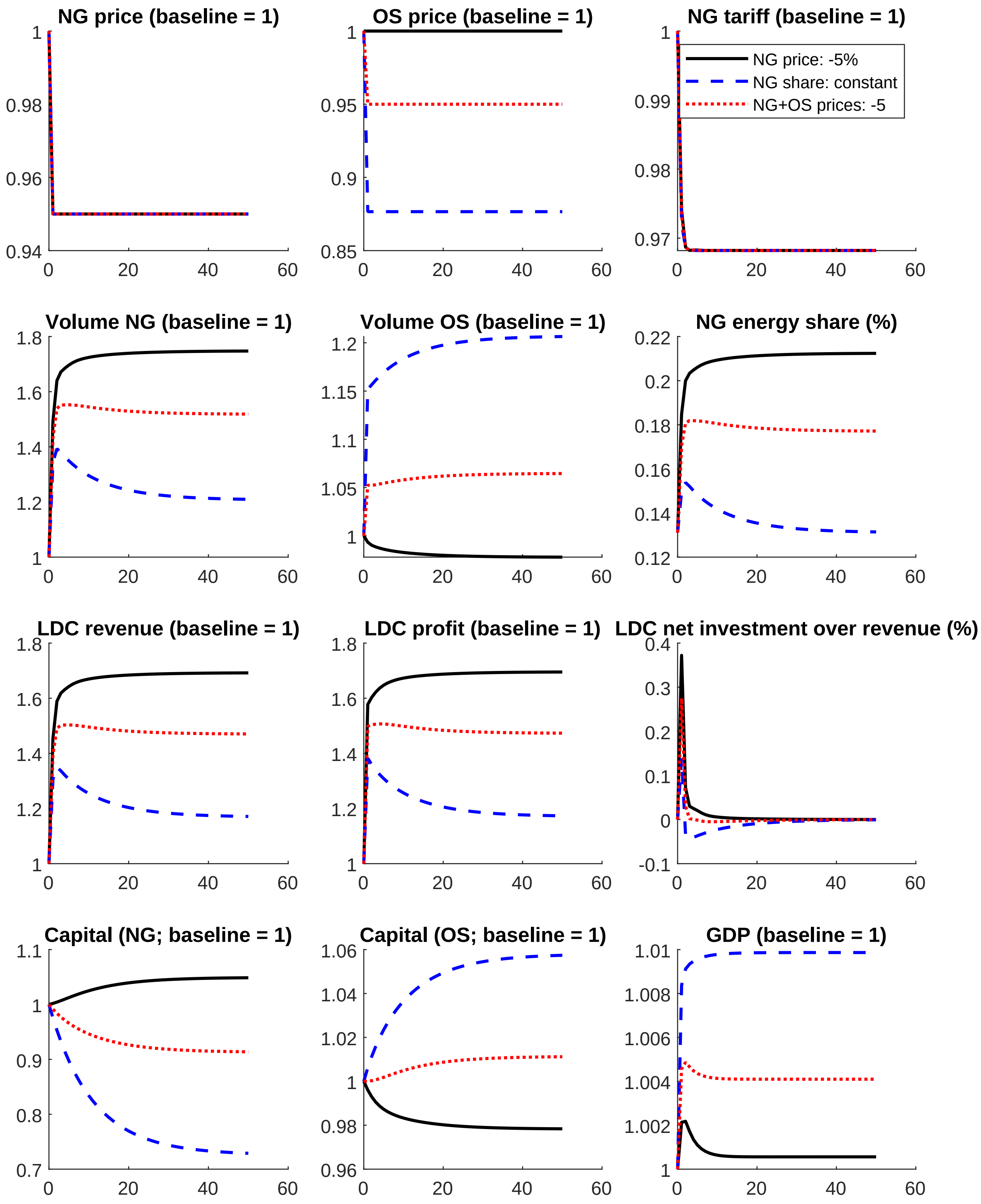

Figure 2.8: Transitions for Naturgy Rio Capital

2.B.8 Naturgy Rio Interior

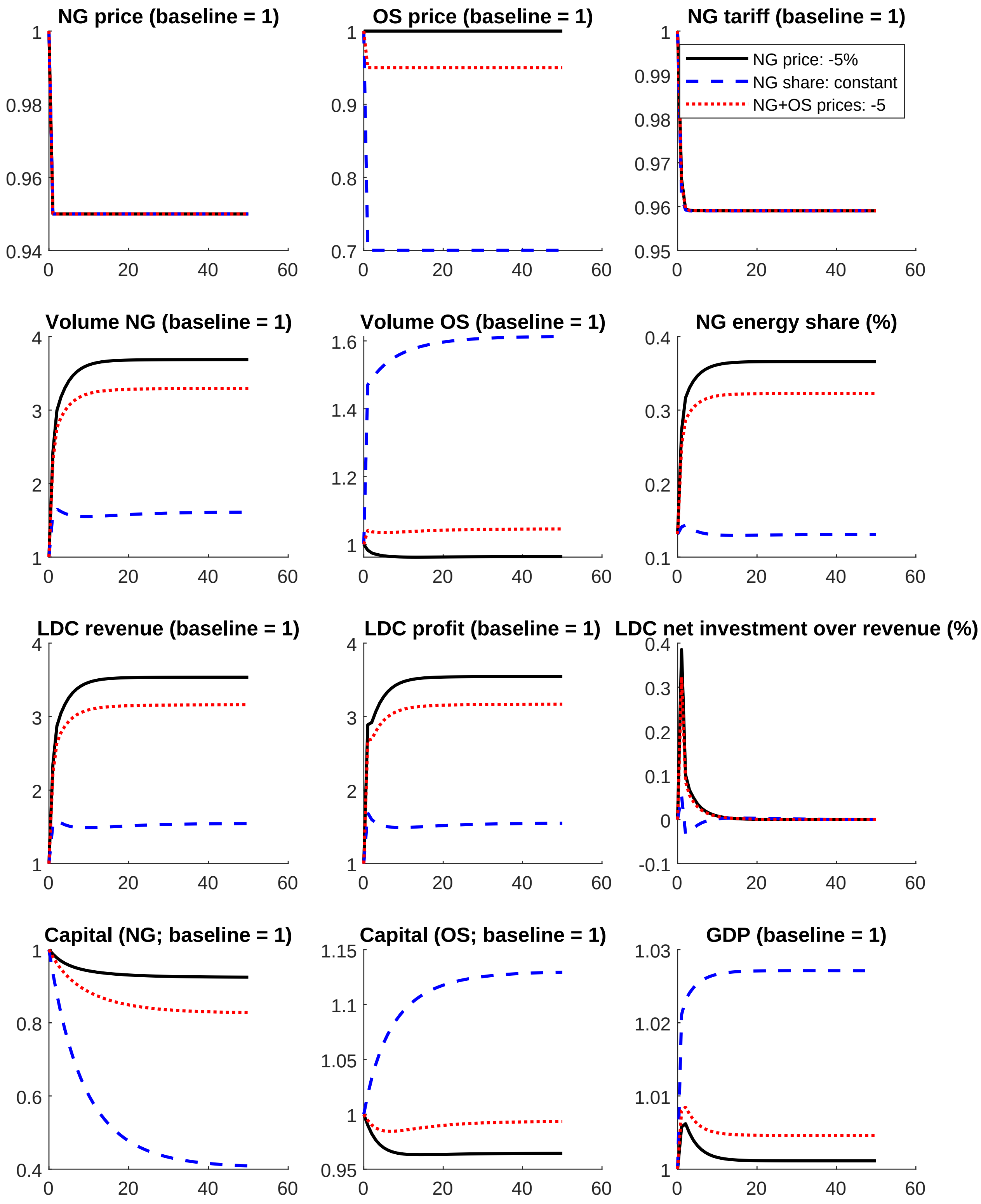

Figure 2.9: Transitions for Naturgy Rio Interior

2.B.9 Gasmig

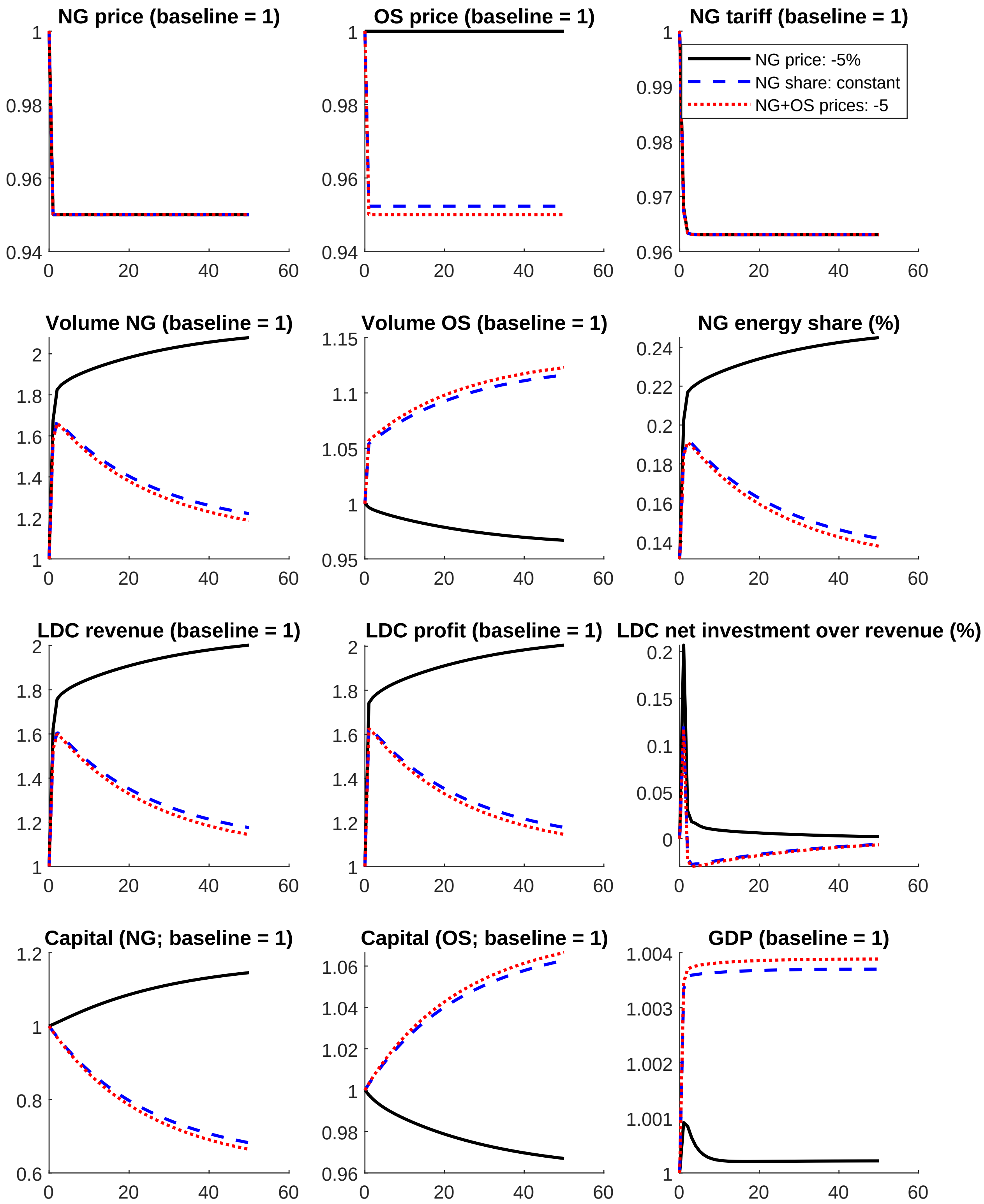

Figure 2.10: Transitions for Gasmig

2.B.10 MSGás

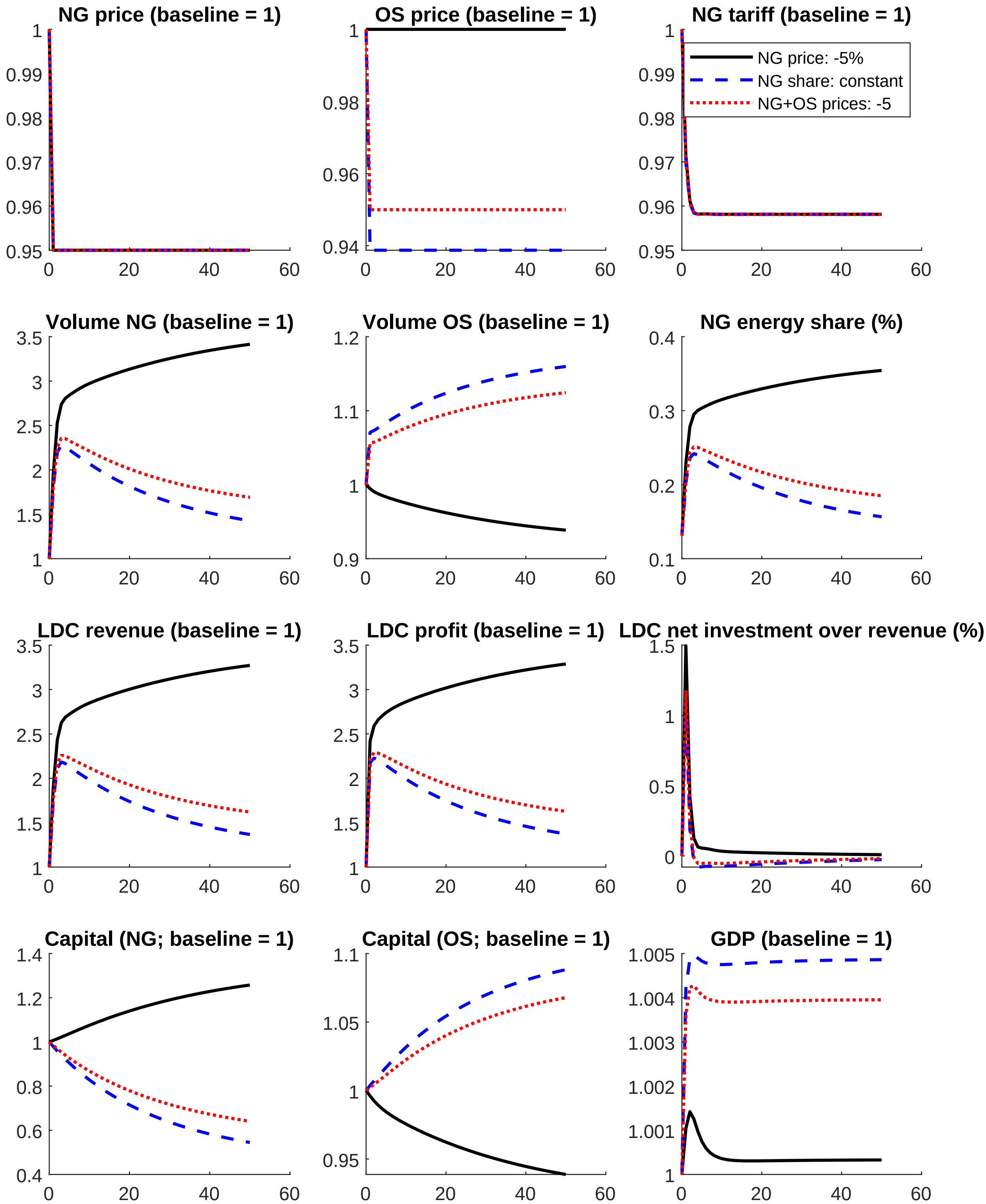

Figure 2.11: Transitions for MSGás

2.B.11 Bahiagás

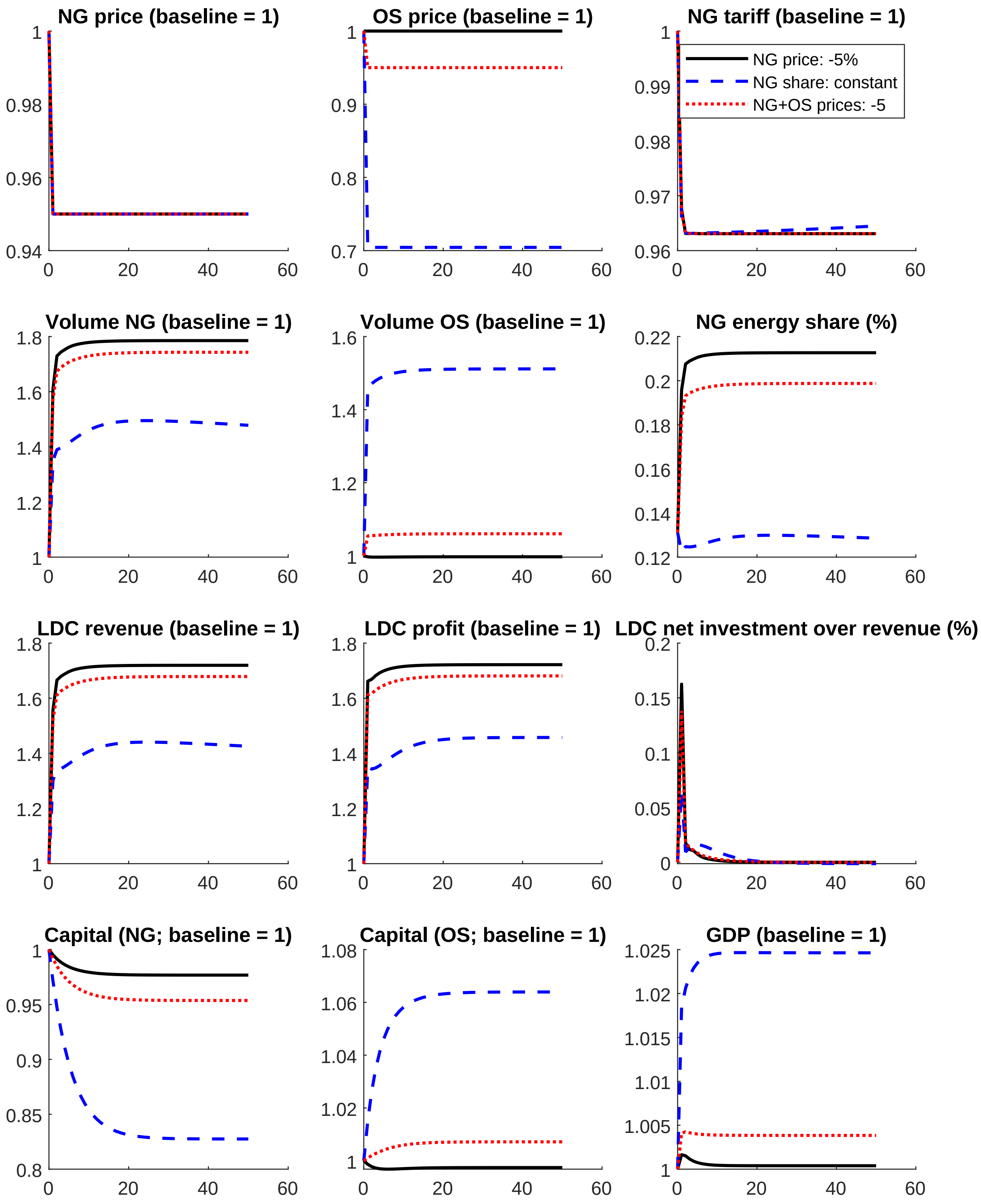

Figure 2.12: Transitions for Bahiagás

2.B.12 Copergás

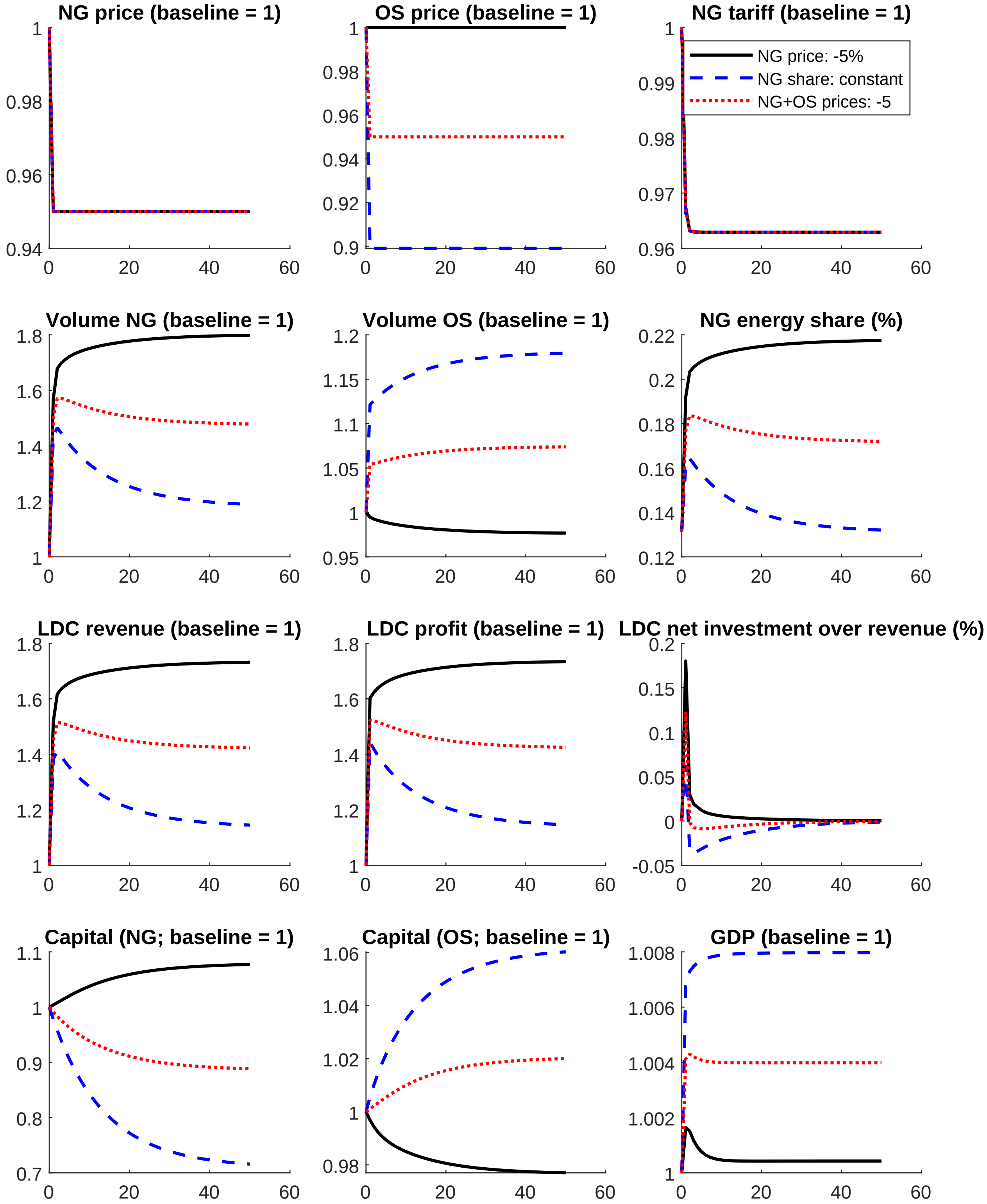

Figure 2.13: Transitions for Copergás

Chapter 3

Heterogeneity and the Energy Consumption of Brazilian Households: A Structural Analysis

Abstract

This paper develops a structural economic model of the residential sector of an economy in which households with different income levels consume goods that use electric energy as an input. The price of energy is non-linear and depends on one's energy demand. The model parameters are disciplined using rich Brazilian consumption micro data at the household level. The data exhibits substantial heterogeneity of expenditures on electric appliances and energy across the different income deciles, and the model is able to capture these features. We use the calibrated model to perform a variety of counterfactuals. The results suggest that the impact of changes in prices and income varies substantially across income groups. We also study the adoption of a new technology. In particular, the introduction of more energy-efficient fluorescent light bulbs is especially helpful to poorer households, despite the bulbs' higher cost.

3.1 Introduction

The electrical energy requirement of the residential sector depends on the energy needed to support several pieces of household equipment that attend to a family's various needs, such as lighting, refrigeration, water heating, air conditioning, cooking, etc. [1] Moreover, households differ in many aspects, with income being a particularly important differentiator, and the equipment and energy demands of households can vary substantially. This heterogeneity takes center stage in this paper. We develop a structural model with heterogeneous households that demand several different types of electric equipment and consequently pay for their energy use. We discipline the parameters of the model using rich Brazilian micro data and use it to conduct a variety of counterfactuals. In particular, we study how households respond to different prices, different income levels, and the introduction of new, more energy-efficient technologies.

To be more precise, we construct a structural economic model that represents the final uses to which Brazilian households put the electricity they consume. The model is inhabited by agents who are heterogeneous with respect to their income, and which represent different deciles of the Brazilian population. These families choose to buy a myriad of equipment for different purposes, all of which use electricity. Each of these pieces of equipment may use more or less energy according to how powerful it is. Families make decisions after observing their income and the price of different equipment, as well as the price of energy (which is a non-linear function of the household's consumption).

The model is calibrated using rich micro data from the Brazilian Expenditure Survey (Pesquisa de Orçamento Familiar, henceforth POF), conducted by the Brazilian Institute of Geography and Statistics (IBGE). The structural preference parameters are calibrated by targeting expenditures equipment and energy for households of different income levels. We then run counterfactuals that change income or energy prices, as well as which observe the introduction of a new, more energy-efficient technology, namely fluorescent light bulbs.

The results from the calibrated model show that households' energy demand after these changes in income and prices is somewhat inelastic when viewed in the aggregate. However, this masks substantial heterogeneity across the different income deciles. For instance, richer households in particular are more elastic. Another example is that when more energy-efficient fluorescent light bulbs are introduced, households face an interesting

[1] This chapter was published at the Brazilian Review of Econometrics, volume 39, year 2019.

double-edged scenario: the new bulbs use less energy but are more expensive. Households across all income deciles respond by consuming more light but spending less for energy. This leads to a reallocation of expenditures across all the different goods the household buys, including those that do not use electricity. The changes are particularly pronounced for poorer households, which spend a higher fraction of their income on energy for lighting purposes. These results highlight the importance of modeling household heterogeneity when studying energy consumption.

It is essential to have models that are able to provide a detailed description of energy consumption patterns for households. These models can be very useful in designing public policies for energy transition that will lead to sustainable development without welfare losses for households. This paper thus aims to analyze the impacts of income and price variations on households' energy consumption using a structural economic model with heterogeneous agents, and which is calibrated to Brazilian data.

Structural studies of the energy sector (especially when dealing with heterogeneous agents) are scarce, especially in a developing country like Brazil. Most studies focus on income inequality and usually only consist of analyses of historical data.[2] Other studies analyze electricity consumption in the aggregate, paying attention only to the relation between energy demand and macroeconomic, demographic, and climate variables.[3] Most of these papers highlight the inelasticity of households' electricity demand due to energy prices and income changes, and the impact of this inelasticity on the formulation of guidelines to public policies. Although these studies help us understand the energy consumption patterns of different households, they usually do not develop a decision-theoretic model with technological detail, which is essential for proposing energy efficiency and greenhouse gas mitigation policy guidelines. Therefore, effective policy analysis requires not only energy models that describe the electricity consumption of the residential sector, but that also describe the different final uses for the energy.

This paper therefore aims to analyze how changes in the economy affect Brazilian households' electricity consumption patterns, with heterogeneity playing a starring role.

[2] For example: Vanin, Graca, and Goldemberg (1981); Arouca (1982); Bôa Nova (1985); Lins (1988); Cohen (2002); Cohen, Lenzen, and Schae er (2005); Achão (2009); Schae er et al. (2003); Schae er (2008); Morello (2010); Morello, Schmid, and Abramovay (2011); Weiss (2015).

[3] See, for example, Villareal and Moreira (2016), Schutze (2015), Dias et al. (2015), Achão (2009), DePaula and Mendelsohn (2010), Schmidt and Lima (2004), Andrade and Lobão (1997), Jannuzzi and Schipper (1991), Modiano (1984).

This analysis is important, since the residential sector is an important player in the electricity market, responsible for 25.6% of the Brazil's electricity consumption in 2016, second only to the industrial sector (EPE (2017)). In addition, according to Cohen (2002), Cohen, Lenzen, and Schaeffer (2005), Achão (2009), and Weiss (2015), there is a significant heterogeneity of electricity consumption patterns between households from different income groups. Achão (2003), Schaeffer et al. (2003), and Januzzi and Swisher (1997) estimate energy demand for the Brazilian residential sector. All of these authors apply a simplified approach, taking into account factors such as demography and income inequality. However, they do not develop a structural approach able to conduct counterfactuals like we do.

This article consists of four sections besides this introduction. The next section describes the data. Section 3.3 develops the economic model, and Section 3.4 discusses how the model is calibrated. Section 3.5 reports the results from the counterfactual analyses. Finally, Section 3.6 concludes.

3.2 Data

Despite decreasing since around 2000, the level of income inequality in Brazil is still very high (Barros, Foguel, and Ulyssea (2007)). Figure 3.1 reports the average household income (in 2009 reais) for each decile of the Brazilian population, using data from POF. The top decile makes, on average, about 30 times more than the poorest decile.

Data for household expenditure consumption and equipment possession are available from POF. PROCEL supplies data on average power of equipment and average length of use per household.[4] Summary statistics for this data are reported in Table 3.1.

The price of energy in Brazil varies according to the energy supplier of each region. Since in the structural model described below there is no regional variation, we opted to include an average price for the entire country that depends on energy consumption. For this, we use data from ANEEL (2017). The average price was calculated as a weighted average across the prices of all different suppliers, weighted by the number of consumers each supplier has. The pre-tax price is constant (at 0.30 reais per kWh). However, the tax rate varies within eletricity consumption bands, yielding a non-linear step pricing

[4] Data from PROCEL can be found at http://www.procelinfo.com.br/main.asp

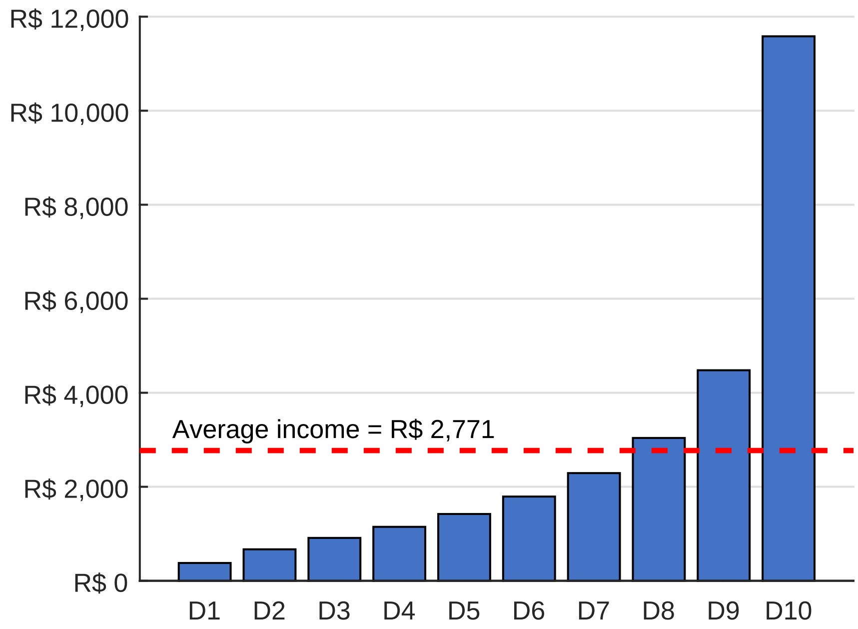

Figure 3.1: Average household income by decile - Brazil (Source: POF, 2009)

Equipment	Av. power (Watts)	Av. usage (hours/year)	Av. ownership per HH	Av. expenditure (Reais/year)
Refrigerator	53	8640	0.925	93.26
Freezer	66	8640	0.137	8.27
Air conditioner	967	960	0.785	10.24
Microwave oven	1867	90	0.278	14.21
Washing machine	486	144	0.449	46.58
Television	95	1800	0.935	126.33
Electric oven	1000	180	0.114	2.69
Fan	36	1920	0.617	10.29
Eletric shower	4467	150	0.625	3.92
Iron	1200	144	0.785	6.32
Computer	103	1760	0.282	56.01
Lighting	252	1800	0.982	24.30

Table 3.1: Summary Statistics (Source: POF and PROCEL).

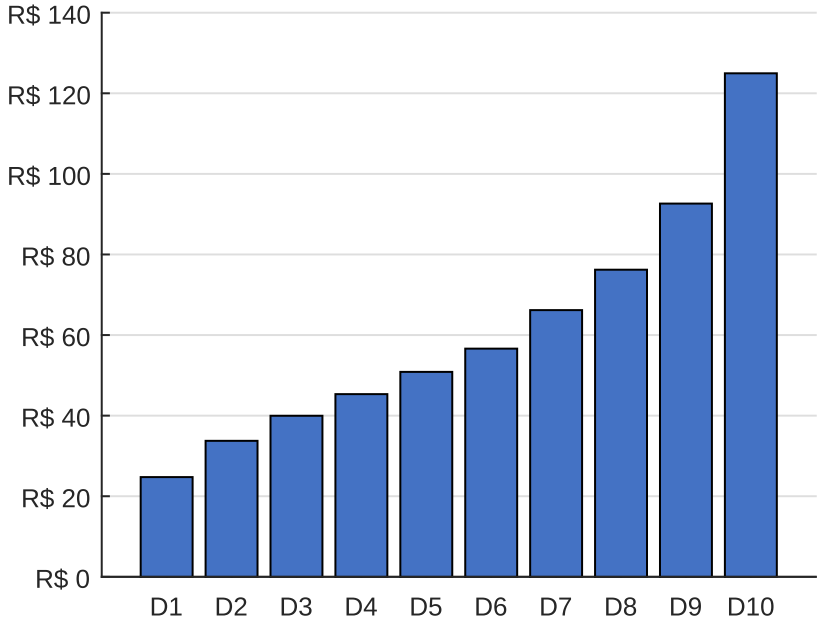

Figure 3.2: Average monthly energy expenditure by income decile (Source: POF, 2009)

schedule.

It is natural that the high levels of income inequality reported in Figure 3.1 translate into substantial variation in consumption as well. Figure 3.2 shows energy expenditures for each decile. It is easy to see that richer families consume much more energy than their poorer counterparts. Households in the richest decile consume about 5 times more than those in the poorest.

Figure 3.3 reports the average annual expenditure of each decile on selected electric equipments. Consumption of all of these items increases with income; however, the increases are not proportional. The ratios between the top and bottom deciles are 6:1 for TVs, 3:1 for refrigerators, 17:1 for washing machines, and 40:1 for computers.

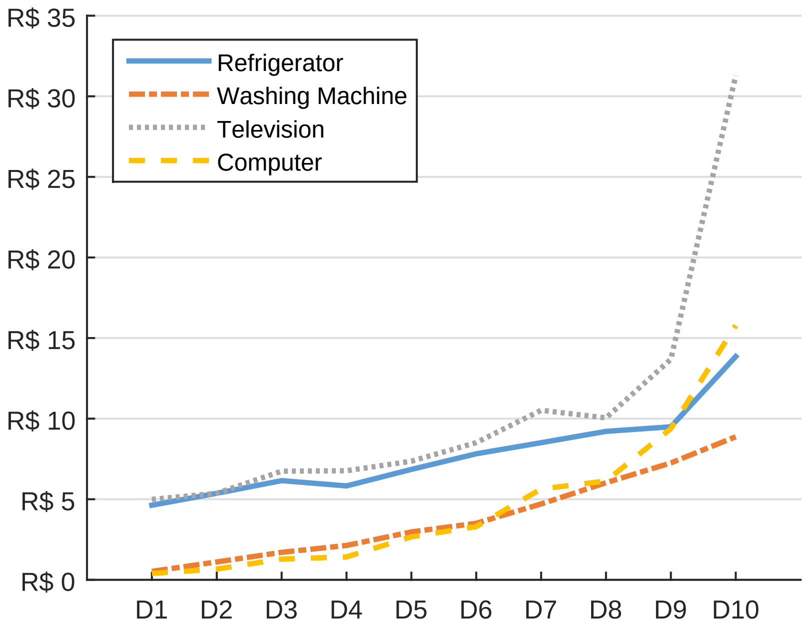

Figure 3.3: Average monthly expenditures on selected electric equipment by income decile (Source: POF, 2009)

By looking at the data described above, one observes great dispersion in both income and expenditures across the different income deciles of the Brazilian population. We also note that energy consumption and expenditures on other equipment does not follow increases in income linearly. These observations motivate the theoretical framework that we develop in the next section. To be more precise, the mathematical model will feature non-homothetic utility and heterogeneous agents.

3.3 Model

This section describes the model with heterogeneous agents. Consider an economy with I agents, heterogeneous with respect to their income $y^i > 0$, where i indexes the household's income class. These I income classes can be seen as representing the different income deciles of the Brazilian economy. These families derive utility from the consumption of different goods. There are $J + 1$ consumption goods; J use energy and 1 does not. Each household values the consumption of these goods according to the following utility function:

$$\log(c^i \quad z_c) + \sum_{j=1}^{J} \alpha_j \log(s_j^i \quad z_j),$$

where c^i is the non-energy good, s^i_j is the use of each energy good j by a family of quantile i. The parameter α_j represents the weight of each good in the household's utility, whereas z_c and z_j are parameters that control the non-homotheticity of preferences, imposing a minimal level of consumption for each good. This type of utility function was also used by Bibas et al. (2015) to represent households' final demand for goods and services, including energy.

The good that does not need energy is the numeraire, with a unitary price. Each of the remaining goods $j \in \{1, ..., J\}$ is rented by the household for the price r_j. The price of each unit of energy paid by the household depends on its total energy consumption, E^i, according to $p(E^i)$. The total service provided by use j is given by s_j, and each unit of energy service j uses t_j units of energy. This means that the total energy consumption of the household i is equal to:

$$E^i = \sum_{j=1}^{J} s^i_j t_j.$$

The household in income quantile i chooses the numeraire $c^i \in \mathbb{R}_+$ that it wishes to consume as well as the vector of consumptions of the other J goods, $\mathbf{s}^i \in \mathbb{R}^J_+$, in order to maximize its utility. The optimization problem for agent i can thus be described as:

$$\max_{c^i,\mathbf{s}^i} \quad \log(c^i - z_c) + \sum_{j=1}^{J} \alpha_j \log(s^i_j - z_j)$$

subject to

$$c^i + \sum_{j=1}^{J} s^i_j \left(p(E^i)t_j + r_j\right) \leq y^i$$

$$E^i = \sum_{j=1}^{J} s^i_j t_j$$

$$c^i \geq z_c, \quad s^i_j \geq z_j \quad \forall j = 1, \ldots, J.$$

In order to gain some insight about the properties of the model, in the following subsection we discuss the particular case in which the energy tariff is linear. This case is interesting to investigate because there is an analytic solution to it. But in the numerical experiments described in Sections 3.4 and 3.5 we will use non-linear tariffs.[5]

3.3.1 Linear Price of Energy

Let us consider the special case in which the energy price is linear; that is, $p(E^i) = p$ is constant. In order to guarantee the existence of a solution, we must impose the following restrictions on the parameters:

$$\alpha_j \geq 0 \quad \forall j = 1, \ldots, J$$

$$z_c + \sum_{j=1}^{J} z_j \Phi_j < y^i \quad \forall i = 1, \ldots, I$$

where $\Phi_j = pt_j + r_j$. The first restriction, on the utility weights α_j, guarantees that none of the goods is actually a bad. That is, it guarantees that each good has a positive marginal utility. The second restriction, on the utility costs z_c and z_j, guarantees that the inequalities $c^i \geq z_c$ and $s^i_j \geq z_j$ are always true.

Since the model features a Stone-Geary utility function with a linear expenditure system, the optimal quantities can be explicitly obtained from the first order conditions and the budget constraint:

$$c^i = z_c + \frac{1}{1 + \sum_{l=1}^{J} \alpha_l} \left(y^i - z_c - \sum_{l=1}^{J} z_l \Phi_l \right)$$

$$s^i_j = z_j + \frac{1}{\Phi_j} \left(\frac{\alpha_j}{1 + \sum_{l=1}^{J} \alpha_l} \right) \left(y^i - z_c - \sum_{l=1}^{J} z_l \Phi_l \right) \quad \forall j = 1, \ldots, J.$$

Substituting c^i and $\mathbf{s}^i$ in the agent's objective function, we can write the indirect utility V^i:

$$\begin{aligned} V^i = & \left(1 + \sum_{j=1}^{J} \alpha_j\right) \log\left(y^i - z_c - \sum_{l=1}^{J} z_l \Phi_l\right) - \sum_{j=1}^{J} \alpha_j \log\left(\Phi_j\right) \\ & + \sum_{j=1}^{J} \alpha_j \log\left(\alpha_j\right) - \left(1 + \sum_{j=1}^{J} \alpha_j\right) \log\left(1 + \sum_{l=1}^{J} \alpha_l\right). \end{aligned}$$

[5] For the case of non-linear tariffs, with $p\left(E^i\right)$ as a non-constant function, an analytic solution is not available in general. Therefore, numerical solutions for the optimization problem are more suitable. We used the first-order conditions of the problem, together with algorithms of multidimensional root-finding, to determine a numerical solution for c^i and $\mathbf{s}^i$.

Note that, except when $z_c = 0$ and $z_j = 0$ for all j, the indirect utility is non-separable on income. That is, income non-trivially affects the agent's decisions. To better illustrate this point, consider the case when $J = 1$, $\alpha = 1$, and $z_c = 0$. Figure 3.4 shows the behavior of the fraction of income spent in energy. When $z_1 = 0$, the household spends half of its income in energy, regardless of income level. However, when $z_1 = 0.1$, this fraction depends on the level of income, approaching 1 when income is low but decreasing back to 0.5 as income level rises. This effect is important, because it allows us to model the heterogeneity of behavior for different levels of income. In particular, price and income elasticities will vary across income levels, being lower in magnitude for lower incomes when $z_j > 0$.

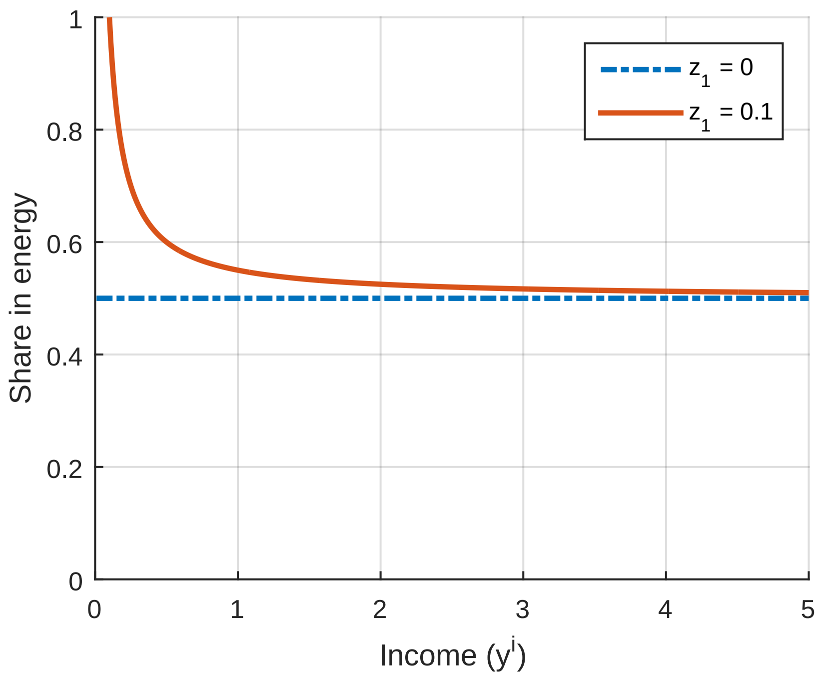

Figure 3.4: Fraction of income spent in energy

3.4 Taking the Model to the Data

In order to run the counterfactual analyses, we must first discipline the structural parameters. First, impose $J = 12$ for the main goods using energy in Brazilian households, namely: the refrigerator, freezer, air conditioner, microwave oven, washing machine, television, electric oven, fan, electric shower, iron, computer and lighting. We assume that each good s_j is measured in units of energy that it uses. We can thus normalize $t_j = 1$ for all j. The income y^i is the average income for each income decile and comes from

POF 2008.

We determine the price r_j for each good j using the following procedure. We first obtain the monthly average expenditure for each of the 12 goods for each income decile, using data from POF (see Table 3.1). We then estimate the monthly energy consumption for each good and each decile, using the simplifying assumption that the period that each good is used and its power are constant across income quantiles. The only variable that changes across deciles is the average ownership. We then compute the percentage of each decile's income that is spent on each good, as well as that good's associated energy consumption.

As for the energy tariff as a function of energy consumption, $p(E)$, Figure 3.5 describes the average energy tariff for different levels of consumption, using values for Brazil in 2008 (see Section 3.2). The differences between bands of consumption are due to different energy consumption tax rates. Since the tariff bands describe a staircase function, which is not a smooth function because of its discontinuities, our approach was to approximate the function with a cubic polynomial.[6]

As was mentioned, the electricity demand of the residential sector is composed of the sum of the energy requirements of several different pieces of household equipment, which serve different functions. The electricity requirement for each of the individual types of equipment was estimated using a Bottom-up model adapted from Januzzi and Swisher (1997). The annual total electricity requirement for each type of household equipment is calculated taking into account the average tenure of the specified equipment, its average power, and its average length of usage per year. The information for the average tenure for equipment within a household for the different income deciles also came from POF 2008. Data from the National Energy Plan (EPE (2008)) and from the Assessment of the Energy Efficiency Market in Brazil—Tenure of Equipments and Their Use Patterns in the Residential Sector (PROCEL (2007)) was used for average power and average usage per year (see Table 3.1). The data was used to calculate monthly energy consumption and equipment expenditures for different uses and levels of income.

[6] The resulting polynomial gave us the function $p(E) = 1.8205287914064 \quad 10^{-9} \quad E^3$ $2.2253130146168 \quad 10^{-6} \quad E^2 + 0.000922873215071064 \quad E + 0.316134355184748$.

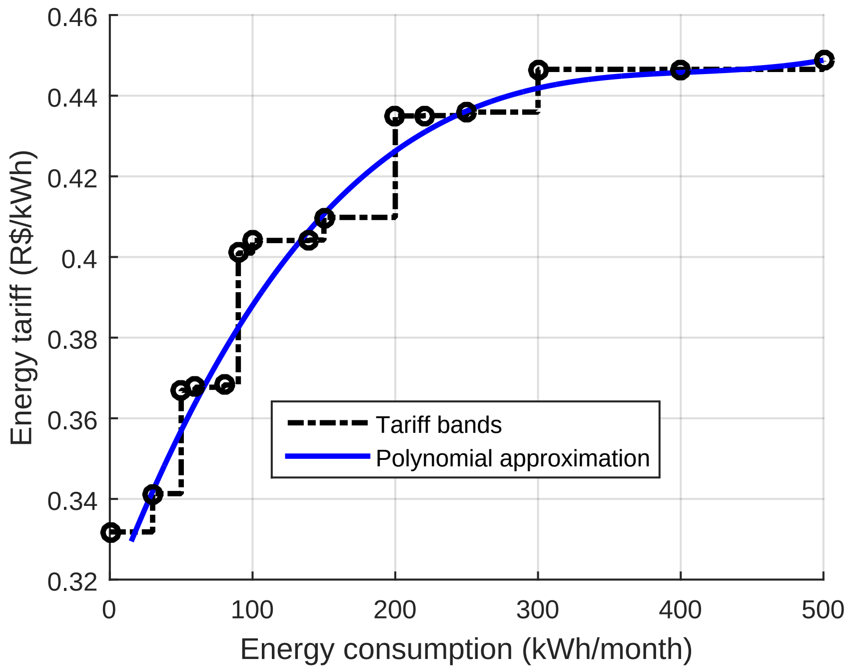

Figure 3.5: Energy tariff behavior among levels of consumption.

We turn now to the structural parameters of the model. Regarding the agents' preferences, we have 25 parameters, namely:

- (1 parameter) The disutility of non-energy good consumption: z_c.
- (12 parameters) The relative preference weight for each energy use: α_j, $j = 1, \ldots, 12$.
- (12 parameters) The disutility of each energy use: z_j, $j = 1, \ldots, 12$.

In order to discipline these parameters, we target 130 statistics in the data:

- (120 moments) Monthly equipment expenditures for each of the 12 energy uses and for each income decile.
- (10 moments) Monthly energy consumption for each income decile (10).

We take as given the average income for each decile computed using POF 2008 data.

We then adjust the parameters in order to minimize the relative distance between the data moments and their model counterparts. Formally, let $\theta = (\alpha^0, z^0)^0$ be the 25 1 vector that contains all preference parameters α_j, z_c, and z_j. Denote by M_d the 130 1 vector of data targets used in the calibration, $M_m(\theta)$ the model counterparts given the parameter vector θ, and W, a weight matrix. For each descriptive statistic k, the relative deviation between data ($M_{d,k}$) and model ($M_{m,k}(\theta)$) statistics is given by

$$\frac{M_{m,k}(\theta) - M_{d,k}}{M_{d,k}}.$$

The calibration procedure minimizes the sum of squared relative deviations, that is,

$$\hat{\theta} = \arg\min_{\theta} \sum_{k=1}^{130} \left(\frac{M_{m,k}(\theta) - M_{d,k}}{M_{d,k}} \right)^2.$$

The advantage of using relative deviation instead of absolute deviation is that it compensates for the different magnitudes among the descriptive statistics. For example, the expenditures are much higher for the tenth decile than for the first decile. If we used absolute deviation, we would be giving more weight to deviations in higher income levels than lower levels. Relative deviation compensates for this effect, giving more weight for lower magnitudes.

Equivalently, we can also write down the calibration problem in a matricial form:

$$\hat{\theta} = \arg\min_{\theta} (M_m(\theta) - M_d)' \mathbf{W} (M_m(\theta) - M_d),$$

where the weighting matrix $\mathbf{W}$ is given by:

$$\mathbf{W} = \begin{bmatrix} M_{d,1}^{2} & 0 & \dots & 0 & 0 \\ 0 & M_{d,2}^{2} & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & M_{d,129}^{2} & 0 \\ 0 & 0 & \dots & 0 & M_{d,130}^{2} \end{bmatrix}.$$

3.4.1 Model Fit

The calibrated parameters are given in Table 3.2. The comparisons between the data targets and the benchmark model are reported in Figures 3.6 and 3.7. The preference weight parameters, α, are all well below the non-energy goods unitary weight, which is expected since none of these energy uses represents a significant fraction of households' budgets. Since we assumed that the energy service provided by each use is measured by its energy consumption, we cannot use the weights to compare preferences between uses, because each use has different levels of efficiency.

	α	z
Refrigerator	0.00206	21.47993
Freezer	0.00045	2.32375
Air Conditioner	0.00051	0.08928
Microwave Oven	0.00078	0.43872
Washing Machine	0.00154	0.43430
Television	0.00314	6.05674
Electric Oven	0.00016	0.41364
Fan	0.00020	2.46922
Electric Shower	0.00255	12.65511
Electric Iron	0.00035	1.79701
Computer	0.00233	0.24965
Lighting	0.00117	26.98999
Non-energy	-	280.87476

Table 3.2: Parameters of household preferences in the benchmark model.

On the other hand, we can see that the non-homotheticity parameter, z, is useful for describing differences in expenditures for different income deciles. A higher z means a lower ratio between the consumption of rich and poor deciles. For example, lighting has a high z value ($z = 27$), but decile 10 only spends 2.4 times more on energy equipment than decile 1. As for air conditioners, $z = 0.09$, but the equipment expenditure is about 147 times higher for decile 10 than for decile 1. Figures 3.6 and 3.7 show that observed and estimated energy consumption and equipment expenditures for each decile are very similar in level, meaning that the model is adequate to describe the heterogeneity of household consumption and can be used as a tool to analyze different policies, which is done in Section 3.5. Another piece of evidence for the quality of the model is the similarity between the elasticities obtained in the calibrated model and the elasticities described in the literature for Brazil, as discussed in the next subsection.

3.4.2 Elasticities

As with other papers about the elasticity of the Brazilian household electric energy requirement (Modiano (1984); Schmidt and Lima (2004); Andrade and Lobão (1997);

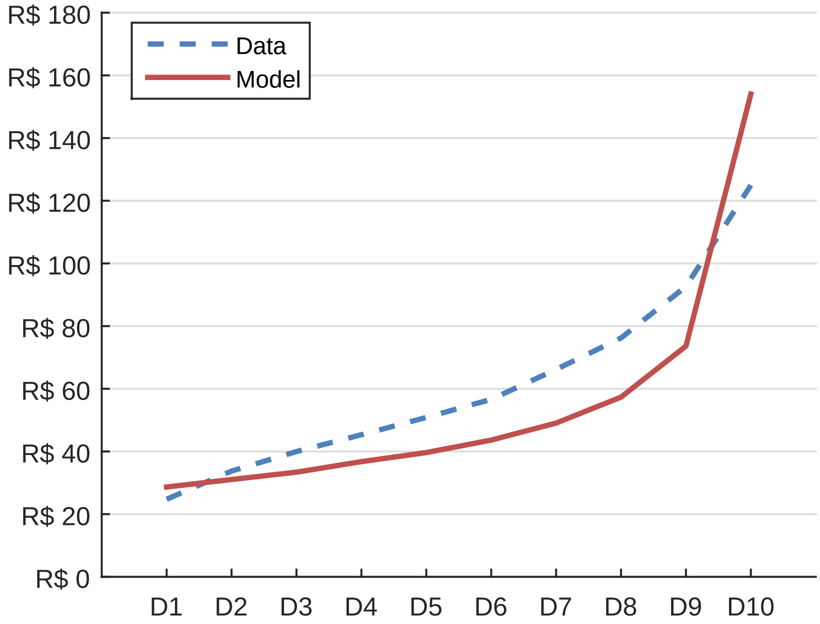

Figure 3.6: Observed and estimated average monthly energy expenditures by income decile.

Schutze (2015); Villareal and Moreira (2016)), our results show that the average Brazilian household is relatively inelastic to energy prices and income changes. Therefore, electric energy consumption responds less than proportionally to changes in prices and income. The average electricity price and income elasticity found were, respectively, -0.30 and 0.49, as shown in Table 3.3.[7]

[7] In order to calculate the elasticities, we ran the calibrated model with energy prices and income values increased by 1%, for each decile. The elasticities are how much, in percentage points, the energy consumption changed.

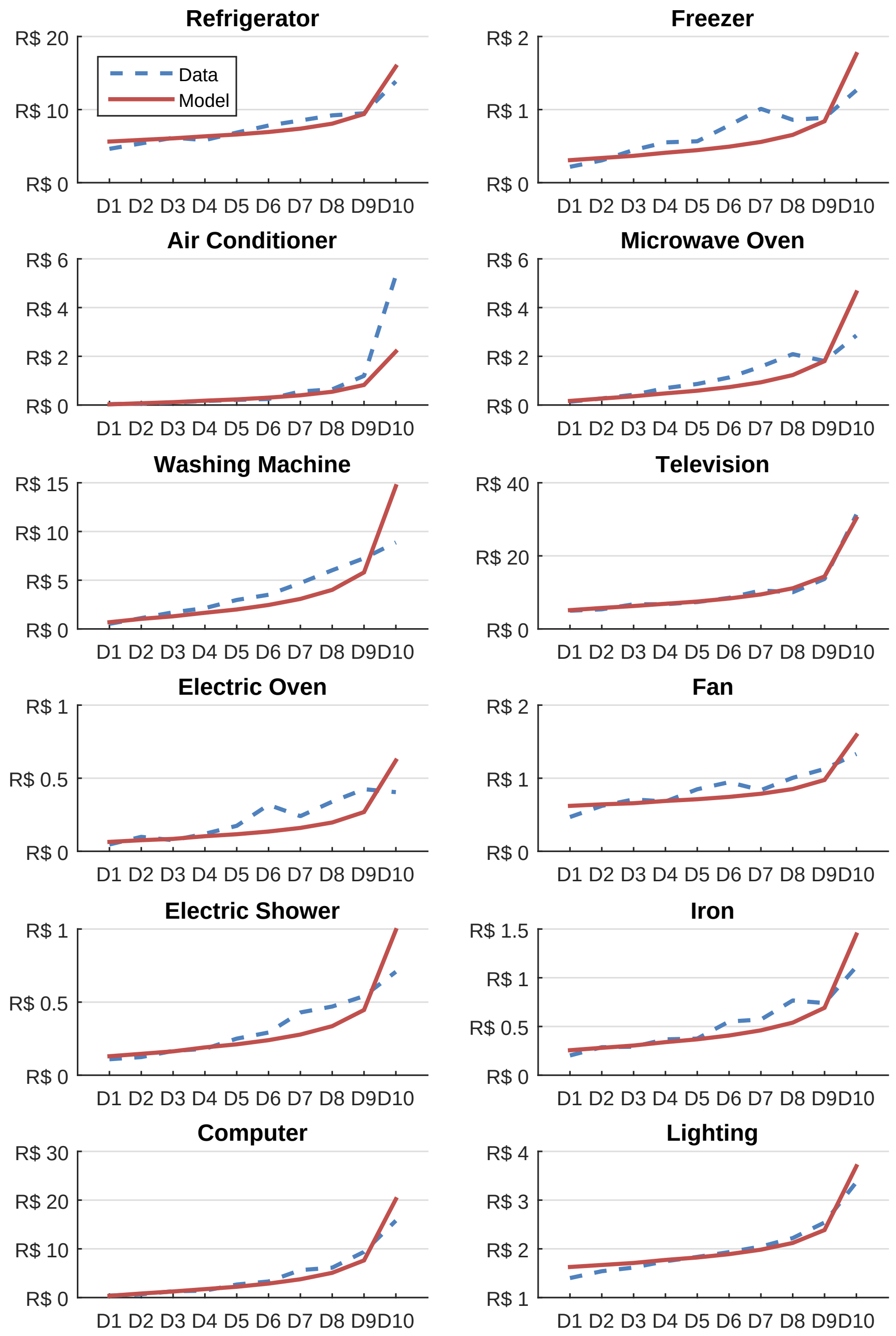

Figure 3.7: Observed and estimated average monthly expenditures on selected electric equipment by income decile.

Decile	Price Elasticity	Income Elasticity
D1	-0.01706	0.098083
D2	-0.06525	0.163507
D3	-0.12001	0.246972
D4	-0.14438	0.289849
D5	-0.17775	0.335673
D6	-0.21671	0.389180
D7	-0.26022	0.448933
D8	-0.31148	0.519313
D9	-0.38063	0.614273
D10	-0.51924	0.804621
Average	-0.29524	0.494357

Table 3.3: Price and income elasticities for the calibrated model.

However, it is important to note that implied elasticities in the model for energy consumption are quite different across income deciles. Poorer households in Brazil are more inelastic to energy prices and income changes than households from the high-income deciles. Considering electricity price changes, a one percent increase in electricity pricing causes the consumer from the lowest income group (D1) to reduce the energy consumption in their household by just 0.02%, whereas, in the case of households from D10, the reduction of energy consumption is greater than 0.50%.

On the other hand, households tend to be more elastic and respond with more significant energy consumption variations when considering income changes than pricing changes. For instance, a one percent increase in income induces an increase of 0.10% in the energy consumption for the lowest income decile (D1), while households in the highest income group (D10) increase their energy consumption by 0.80%.

3.5 Quantitative Experiments

With the calibrated model, it is possible to perform various counterfactual analyses to infer the impact of different scenarios on the household's energy demand. We also study the impact of the introduction of more energy-efficient fluorescent light bulbs.

We first consider two counterfactual scenarios:

1. A tariff reduction of 40%;[8]

2. A rise in income of 40%;

Let us first look into the expenditure composition. Figure 3.8 shows that energy and equipment weigh more heavily on the budgets of poorer deciles, since households in decile 1 (D1) spend 12% of their income on energy and electrical equipment, while for D10 this number is only 2%. If we take a closer look at the different uses that energy is put to, the categories where households spend the most on average are lighting, refrigerators and electric showers. For each income decile, Table 3.4 illustrates share of each of these three categories as a percentage of total expenditures. It is clear that the share of lighting and refrigerators decreases as income increases, while the inverse is true for electric showers. The expenditure composition for the counterfactual scenarios are displayed in Table 3.5. It shows that there is little change in the composition over the scenarios, except for decile 1, where equipment and energy expenditures decrease from 12% to 9% in both counterfactuals.

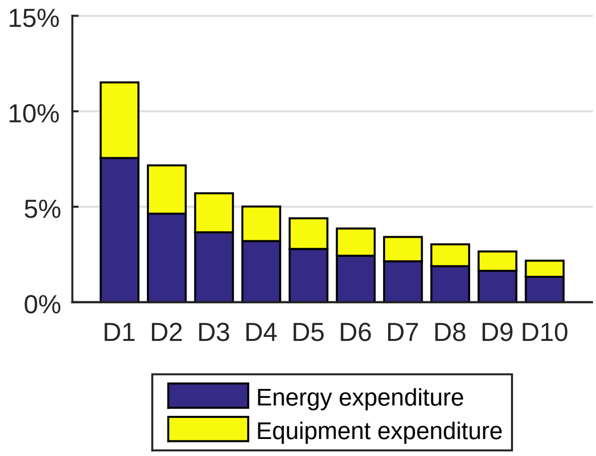

Figure 3.8: Benchmark - energy and equipment expenditures as % of income.

[8] In this scenario, tariff reduction considers the multiplication of the tariff polynomial, $p(E)$, by 0.6.

Decile	Lighting	Refrigerator	Electric Shower
D1	27%	31%	11%
D2	25%	30%	12%
D3	24%	29%	12%
D4	23%	27%	13%
D5	22%	26%	13%
D6	21%	25%	14%
D7	19%	24%	15%
D8	18%	22%	15%
D9	16%	21%	16%
D10	12%	17%	18%

Table 3.4: Use expenditures as % of total equipment and energy expenditures.

Decile	Benchmark	Tariff - 40%	Income + 40%
D1	12%	9%	9%
D2	7%	6%	6%
D3	6%	5%	5%
D4	5%	4%	4%
D5	4%	4%	4%
D6	4%	3%	3%
D7	3%	3%	3%
D8	3%	3%	3%
D9	3%	2%	2%
D10	2%	2%	2%

Table 3.5: Equipment and energy expenditures as % of income.

As for energy consumption, according to Table 3.6 and Figure 3.9, changes are more prominent for higher-income deciles than for lower-income deciles. However, decile 1 responds more substantially to a rise in income (4%, against 1% for the tariff reduction), while decile 10 is more responsive to the tariff change (31%, against 24% in the income change scenario). All deciles increase consumption and, in general, the magnitude of the increase is higher when income is higher, except for decile 4 which has a lower increase than decile 3. The reason for this is the shape of the adjusted tariff polynomial, since the increase would be monotone if the tariff was linear, as shown in Section 3.3.1.

Decile	Tariff - 40%	Income + 40%
D1	1%	4%
D2	4%	5%
D3	9%	10%
D4	9%	9%
D5	11%	10%
D6	13%	12%
D7	15%	13%
D8	19%	16%
D9	23%	18%
D10	31%	24%

Table 3.6: Energy consumption (% change from the benchmark).

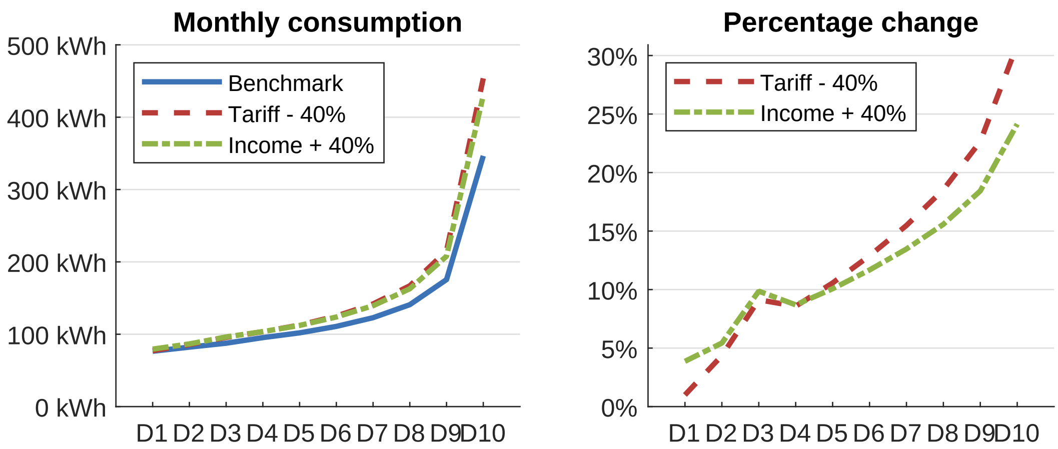

Figure 3.9: Energy consumption.

We can observe the heterogeneity among the different uses comparing the cases of electric showers, computers and air conditioners (Figure 3.10). First, the poorest households hardly consume any energy through computers and air conditioners (less than 1 kWh per month), whereas they consume 14 kWh/month via electric showers. In addition, for these poorest families, energy consumption via computers and air conditioners responds more sharply to changes in income than to changes in tariffs. An increase of 40% in the poorest families' incomes can elevate the energy consumption related to computers by

70% and to air conditioners by 90%. On the other hand, the same income increase would increase the energy consumption related to electric shower by just 7% for the first decile. Although the increase in energy consumption of computers and air conditioners is very high for the first decile, it can be explained by the fact that consumption levels are so low for these uses that any small absolute increase leads to a large relative increase.

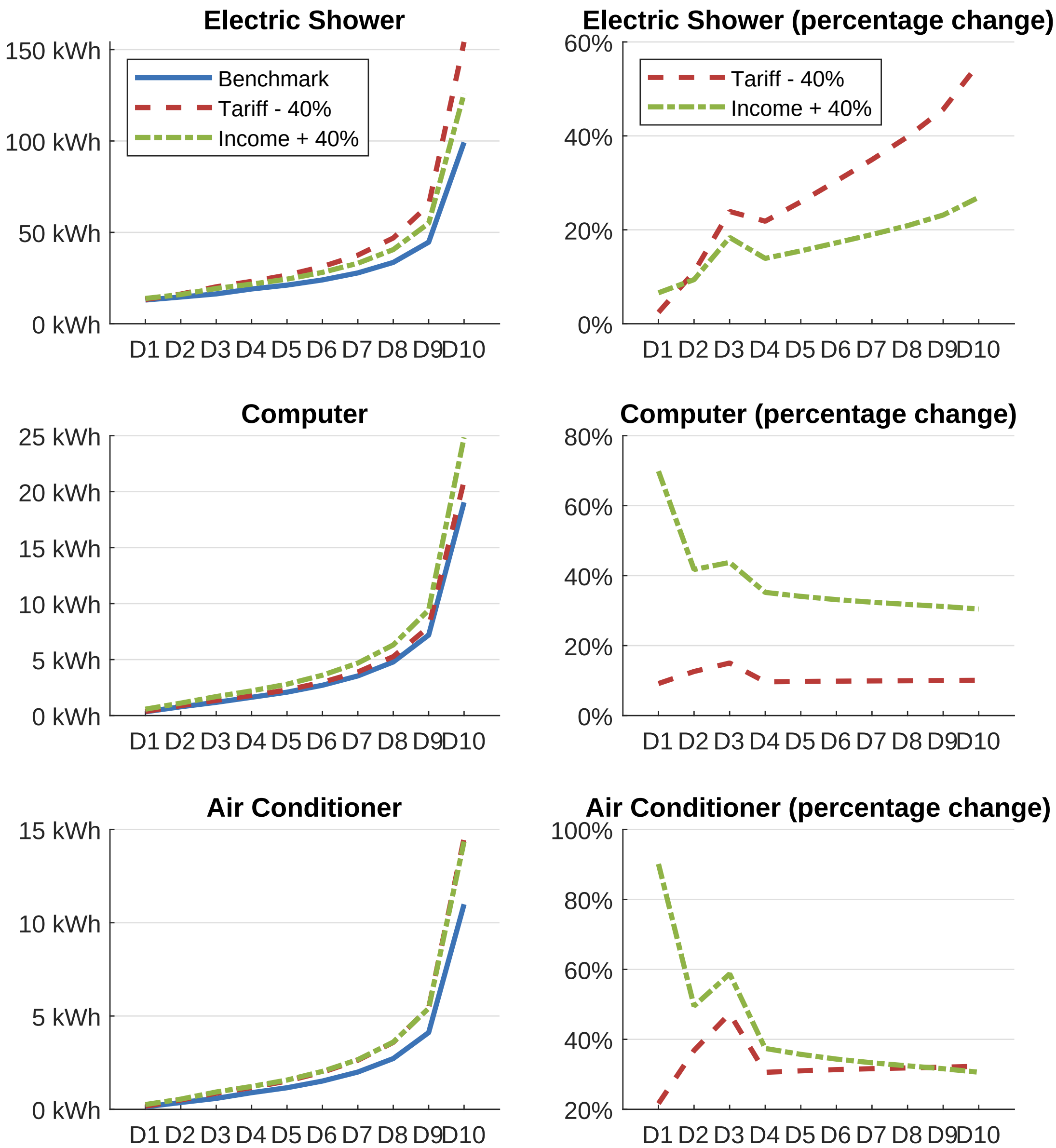

Figure 3.10: Energy consumption for electric showers, computers and air conditioners.

The reduction tariff scenario generates more marked results for poorer households. As shown in the Figure 3.11, the tariff reductions create a reduction of 40% in the poorest households' energy expenditures, whereas an increase of 40% would increase the energy expenditure by nearly 5%.

Therefore, although both scenarios result in more significant changes in the energy consumption of households from the high-income classes, the reduction in the share of the energy consumption expenditures on overall income was more pronounced in the lowest income deciles. As these consumers are more elastic to income changes, the tariff reduction counterfactual results in bigger reductions in the share of energy expenditures compared to total income. Nevertheless, in the case of decile 1, both scenarios generated a reduction in energy consumption expenditures from 11.5% to approximately 8.6% of overall income. In the other deciles, the tariff reduction scenario resulted in even more significant reductions.

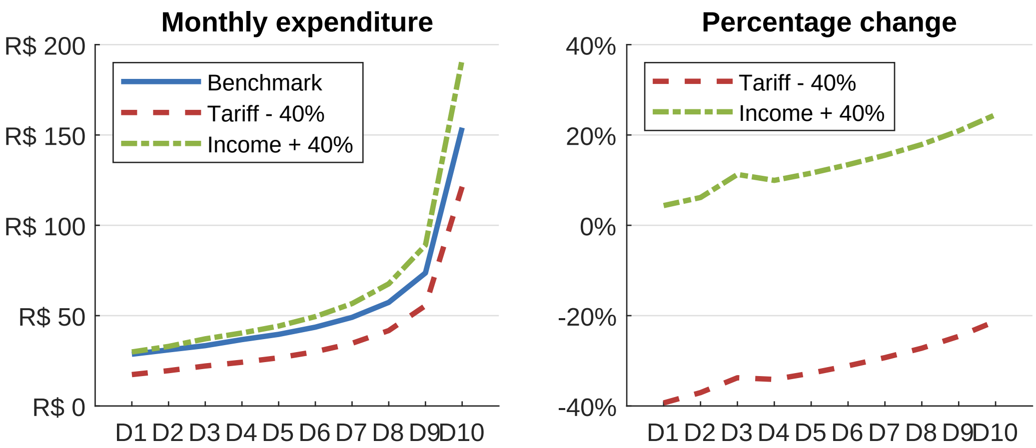

Figure 3.11: Energy expenditure.

Table 3.7 analyzes the effective subsidy on energy created by a 40% reduction of the energy tariff. The second column displays the cost, in 2009 US$, for each household of a specific decile. The third column is the change in energy consumption, and the fourth is the fraction between the second and the third column. The fraction shows how much of the subsidy is reverted to non-energy expenditure. These values show that lower deciles allocate most of the subsidy toward non-energy expenditures, while for higher deciles energy consumption is much more sensitive to the price change. As an illustration, every 1 US$ of subsidy will increase energy consumption by only 0.13 kWh for decile 1, while for decile 2 this number jumps to 2.54 kWh.

Decile	Subsidy (US$/month)	Change in energy consumption (kWh/month)	Change in energy consumption over subsidy (kWh/US$)	Fraction of subsidy reverted to non-energy expenditure
D1	6.05	0.76	0.13	96%
D2	6.80	3.58	0.53	84%
D3	7.70	8.00	1.04	68%
D4	8.43	8.18	0.97	71%
D5	9.28	10.77	1.16	65%
D6	10.46	14.29	1.37	58%
D7	12.07	19.02	1.58	51%
D8	14.53	26.11	1.80	44%
D9	19.32	39.77	2.06	35%
D10	42.23	107.13	2.54	23%

Table 3.7: Subsidy on energy.

3.5.1 Technological Change - Fluorescent Light Bulbs

The model developed here is also capable of analyzing the impact of the adoption of different technologies. For example, here, we consider a scenario where all lighting is provided by fluorescent bulbs, which are a more energy efficient and costly technology than incandescent bulbs. The average level of incandescent and fluorescent bulb possession for the benchmark model was calibrated using Brazilian data from PROCEL (2007). The data shows that Brazilian households had on average 8 light bulbs (4 fluorescent and 4 incandescent), and that LED lamps were still incipient at that time. Therefore, we only considered full adoption of fluorescent lamp for the counterfactual. Based on the average efficiency level of florescent bulbs when compared to incandescent ones, we assume that full fluorescent lamps usage would, on average, consume only 37% of the energy needed to give the same amount of lighting as the benchmark, thus we set $t = 0.37$, since we adopted the convention of measuring energy service in kWh/month on the benchmark, setting t to 1. As for the price of fluorescent light bulbs, we used a 92% increase, based on the market price survey conducted for that study.

Figure 3.12 displays the percent changes in energy consumption and expenditures, both for lighting and total expenditures, across income deciles. The expenditure for light bulbs increased significantly, by 93% for decile 1 and 159% for decile 10, but the decrease in energy expenditures more than compensated for that. For instance, the combined expenditure on energy and equipment for lighting fell by 42% for decile 1 and 25% for decile 10. Since lighting comprises an important share of households' energy consumption—28% in the benchmark model—the impact of this experiment was not negligible over total expenses. Energy expenditures reduced by 24% for decile 1 and 9% for decile 10, and the combined expenditure in energy and all equipment fell by 12% for decile 1 and 3% for decile 10.

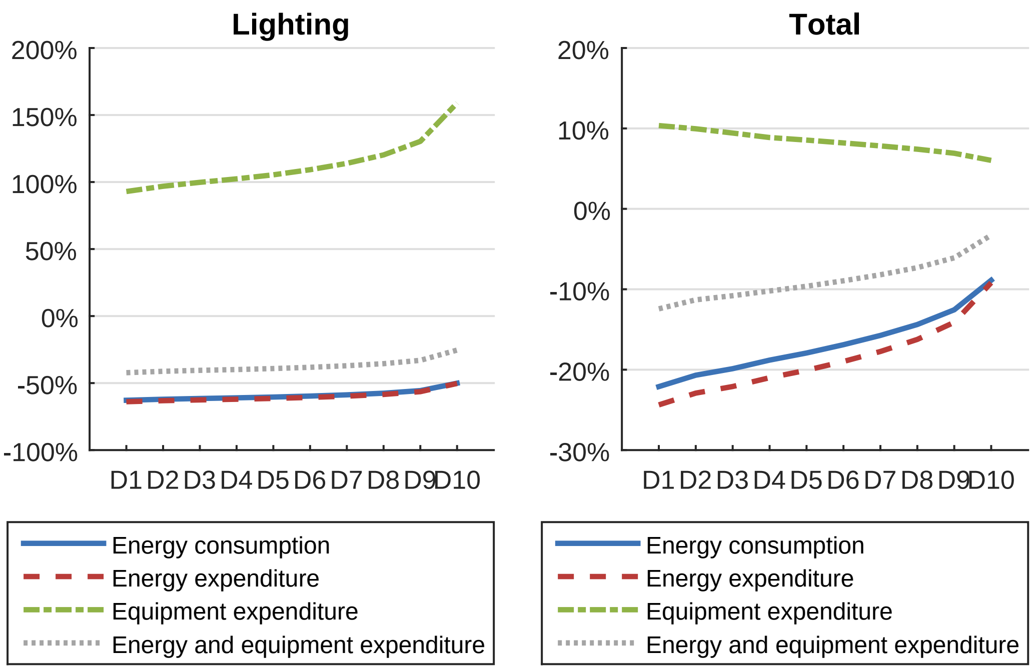

Figure 3.12: Fluorescent lighting – percentage changes from benchmark.

The non-energy expenditure increased modestly for most deciles, but the impact was relatively more pronounced for poorer households. For decile 1, it increased 1.62%, and for decile 2, 0.87%, as shown in Figure 3.13. The energy consumption on all uses except lighting increased slightly for all deciles, meaning that all households were better off in this scenario. This result suggests that technological progress that makes equipment more energy efficient, even though it becomes more expensive, may be welfare-enhancing, especially for poorer households.

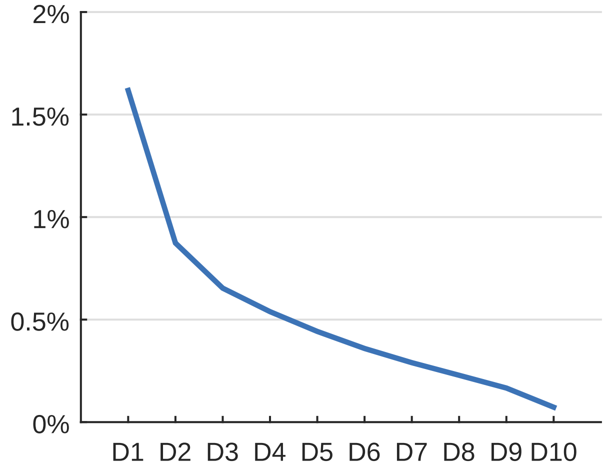

Figure 3.13: Fluorescent lighting – percentage changes on non-energy expenditures.

3.6 Concluding Remarks

This paper develops a heterogeneous agent model in which households choose the consumption of different goods that use energy. We calibrated this model using consumption micro data for the Brazilian economy. We also performed different counterfactuals that changed both income and energy prices. One conclusion from our model is that poorer households in Brazil seem to be somewhat inelastic when it comes to energy consumption.

The framework can also be used to study the impact of adopting new technologies. We study how the introduction of more energy-efficient fluorescent light bulbs affects the demand for energy and the consumption of other goods. The results point to especially important effects among the poorer households in the economy: These households gain from the lower energy expenditures even though the new technology is initially more expensive.

The model developed in this paper can also be used to analyze the impact of different policies, such as the taxation of different goods or energy. Moreover, it is also well-suited to studying the adoption of other technologies. We leave these as potential avenues for future research.

Bibliography

[1] C. C. L. Achão. "Análise da Estrutura de Consumo de Energia no Setor Residencial Brasileiro". *mimeo, COPPE/UFRJ/PPE* (2003).

[2] C. C. L. Achão. "Análise de Decomposição das Variações no Consumo de Energia Elétrica no Setor Residencial Brasileiro". *mimeo, COPPE/UFRJ/PPE* (2009).

[3] T. A. Andrade and W. J. A. Lobão. "Elasticidade renda e preço da demanda residencial de energia elétrica no Brasil". Texto para Discussão IPEA n. 489. 1997.

[4] ANEEL. "Relatórios de Consumo e Receita de Distribuição" (2017).

[5] M. C. Arouca. "Análise da Demanda de Energia no Setor Residencial no Brasil". *mimeo, COPPE/UFRJ/PPE* (1982).

[6] R. P. Barros, M. N. Foguel, and G. Ulyssea. *Desigualdade de renda no Brasil: uma analise da queda recente*. Brasília: IPEA, 2007.

[7] R. Bibas et al. *IMpact Assessment of CLIMate policies with IMACLIM-R 1.0. - Model documentation version 1.1*. France, 2015.

[8] A. C. Bôa Nova. *Energia e Classes Sociais no Brasil*. São Paulo - SP: Ed. Loyola, 1985.

[9] C. Cohen. "Padrões de Consumo: Desenvolvimento, meio ambiente e energia no Brasil." *mimeo, COPPE/UFRJ/PPE* (2002).

[10] C. Cohen, M. Lenzen, and R. Schaeffer. "Energy requirements of households in Brazil". *Energy Policy* 33.4 (2005), pp. 555–562.

[11] G. DePaula and R. Mendelsohn. "Development and the impact of climate change on energy demand: Evidence from Brazil". *Climate Change Economics* 1.03 (2010), pp. 187–208.

[12] T. F. Dias et al. “Elasticidades-preço e renda da demanda domiciliar de eletricidade: estimação econométrica com dados da POF 2008/2009”. MA thesis. Programa de Pós-graduação em Economia – Universidade Federal de Juiz de Fora, 2015.

[13] EPE. *Balanco Energetico Nacional*. Empresa de Pesquisa Energética, 2017.

[14] EPE. *Plano Nacional de Energia 2030*. Rio de Janeiro: Ministério das Minas e Energia, 2008.

[15] G. Jannuzzi and L. Schipper. “The structure of electricity demand in the Brazilian household sector”. *Energy Policy* 19.9 (1991), pp. 879–891.

[16] G. Januzzi and J. Swisher. *Planejamento Integrado de Recursos Energeticos: meio ambiente,Conservacao de energia e fontes renovaveis*. Campinas: Autores Associados, 1997.

[17] M. P. Lins. “Estrutura do Consumo Energético Residencial no Estado do Rio de Janeiro”. *Informacao Tecnica AESP* 0-001/88 (1988).

[18] E. Modiano. “Elasticidade-renda e preços da demanda de energia elétrica no Brasil”. Texto para discussão PUC/RJ n. 68. 1984.

[19] T. F. Morello. “Consumo de lenha e distribuição de renda”. *Informacoes FIPE* (Setembro 2010).

[20] T. F. Morello, V. Schmid, and R. Abramovay. *Rompendo com o trade-o entre combate a pobreza e mitigacao do efeito estufa: o caso do consumo domiciliar de energeticos no Brasil*. Tech. rep. Brasília: IPEA, 2011.

[21] PROCEL. *Avaliacao do mercado de e ciência energetica no Brasil: Pesquisa de Posse de Equipamentos e Habitos de Uso - Ano base 2005. Classe Residencial, Relatorio Brasil*. Rio de Janeiro: Eletrobrás, 2007.

[22] R. Schaeffer. “Elaboração de Ferramenta Computacional para Estimar o Potencial de Conservação de Energia Elétrica em Comunidades de Baixo Poder Aquisitivo”. *Relatorio Tecnico Light* (2008).

[23] R. Schaeffer et al. *Energia e Pobreza: Problemas de Desenvolvimento Energetico e Grupos Sociais Marginais em areas Rurais e Urbanas do Brasil*. Unidad de Recursos Naturales e Infraestructura de La Comisión Económica para America Latina y el Caribe (Cepal), Naciones Unidas, 2003.

[24] C. A. J. Schmidt and M. A. M. Lima. “A demanda por energia elétrica no Brasil”. *Revista brasileira de economia* 58.1 (2004), pp. 68–98.

[25] A. M. Schutze. “A Demanda de Energia Elétrica no Brasil”. PhD thesis. PUC-Rio, 2015.

[26] V. R. Vanin, M. G. Graça, and J. Goldemberg. “Padrões de consumo de energia - Brasil 1970”. *Ciência e Cultura* 33.4 (Abril 1981), pp. 477–486.

[27] M. J. C. Villareal and J. M. L. Moreira. “Household consumption of electricity in Brazil between 1985 and 2013”. *Energy Policy* 96 (2016), pp. 251–259.

[28] M. Weiss. “Análise do Consumo de Energia Direta e Indireta das Famílias Brasileiras por Faixa de Renda”. MA thesis. UFRJ/COPPE, 2015.