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Reforms in the natural gas sector and economic development☆

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ABSTRACT

This paper investigates the short- and long-term effects of increased competition in the provision of natural gas. We build a dynamic general equilibrium model with monopolistic distribution of natural gas and calibrate it to 12 major Brazilian local distribution companies. We find that reductions in the price of natural gas can lead to sustained and significant increases of natural gas in the energy mix. A 5% reduction in the price of natural gas leads to a median increase in the consumption of natural gas of 5.5%, with moderate GDP gains between 0.03% and 0.16%. Our model not only highlights the mechanisms for energy transitions but also shows that moderate declines in natural gas prices can lead to sustained long-term increases in the share of natural gas consumption.

1. Introduction

The energy sector is a fundamental pillar of modern economies, due to the crucial function of energy in the supply chain as an indispensable intermediate input. Consequently, regulatory reforms that alter the market structure and pricing decisions within the energy sector can have substantial spillover effects (Peretto, 1999).[1] Although previous studies have investigated the significance of oil as a vital input in the economy (see, for example, Unalmis et al., 2009 and Bodenstein and Guerrieri, 2011), there is scant literature on the macroeconomic effects of regulatory reforms in the natural gas sector using a general equilibrium framework. To fill this gap, in this paper we build a general equilibrium model to analyze the short- and long-term macroeconomic implications of price adjustments resulting from increased competition within the natural gas sector.

We study the potential effects of natural gas policies in the context of Brazil, which recently brought into force new legislation for the natural gas sector.[2] The so-called New Gas Law laid the groundwork for a thorough reform of the Brazilian natural gas market aiming at fostering competition among suppliers, supporting efficient resource allocations, and reducing domestic industrial prices (de Freitas Benevenuto et al., 2022; Lisbona Romeiro and Amorim, 2022). Crucially, it triggered the end of the national oil company's monopoly (Petrobras) on natural gas production, transportation, and distribution.

We contribute to the literature in several ways. First, we assess the importance of reductions in the price of natural gas relative to the price of other energy sources for energy transitions and GDP. Specifically, a 5% reduction in the price of natural gas leads to significant tariff reductions of between 2.5% and 4.2%, increased natural gas distribution in the short and long run (a median increase of 5.5%), moderate GDP gains between 0.03% and 0.16% in the long run, and an increase in the natural gas share between 0.4 and 0.9 percentage points in the long run.

Second, we show that a reduction in the natural gas price is not enough to increase the share of natural gas in the energy mix. We simulate a reduction of 5% in the price of natural gas and other energies.

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[1] Since this sector is usually composed of a relatively small number of firms with high market power, various regulatory reforms have been implemented in several countries (Cheng, 1997; Poveda and Martinez, 2011; Zhixin and Xin, 2011; Jamasb et al., 2014; Sasana and Ghozali, 2017). For example, in Latin America, we can highlight the cases of Argentina, Brazil, Chile, Colombia, Peru, and Mexico (Rudnick et al., 2005; Pombo and Taborda, 2006; Junior and de Almeida, 2007; Sheinbaum et al., 2011; Eljuri and Johnston, 2014; Diaz, 2021; Duhalt, 2022).

[2] Law No. 14134/2021 was sanctioned in 2021.

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Although this leads to tariff reductions and increased distribution, but the natural gas share declines on average by 0.14 percentage points with moderate GDP gains between 0.38% and 0.44%.

Third, we show that improvements in natural gas efficiency can be a powerful tool for inducing energy transitions. Indeed, natural gas is of significant importance as a flexible and versatile energy source that can complement renewable energy systems. As documented in IEA (2022), natural gas can be used as a backup energy source to address the intermittency of renewable energy production, which can be affected by extreme variations in weather patterns. Another advantage of natural gas is that the infrastructure used for its transportation and storage can be repurposed for other gases such as hydrogen (Melaina et al., 2013).[3] This means that natural gas can serve as a stepping stone toward a fully decarbonized energy system. Moreover, Fried (2018) shows that a carbon tax can induce innovation in green technologies by changing the relative price of fossil energies. If the relative price of natural gas is sufficiently reduced, then it could foster innovation in the sector. We show that an increase of 1% in the relative efficiency of natural gas induces a 1.4 percentage point increase in the natural gas share, which is sustained in the long run.

Our methodological contribution is to build a dynamic general equilibrium model in which a local distribution company (henceforth, LDC) dynamically invests in capacity expansion with investment adjustment costs. LDCs are in charge of distributing natural gas at the regional level and each of them is effectively a monopoly for the consumers of a particular geographic region. Since LDCs are monopolies, they not only consider the price of natural gas production, but also decide in each period the tariff charged for each unit of natural gas distributed. The fact that investments in capacity expansions are dynamic is crucial, since LDCs not only determine the tariff based on the demand curve faced and the operational costs, but they also take into account the funding of an investment schedule when fixing the tariff. Thus, any policy that changes the market structure will have short- and long-run effects, which our model can capture.[4]

We differentiate capital services depending on how they are powered, i.e., by natural gas or other sources. This builds on Atkeson and Kehoe (1999) so that capital services provision requires both raw capital and energy as inputs. Additionally, capital producers are subject to investment adjustment costs, just like the LDCs who invest in capacity expansion. Capital services from both types of energies are bundled and used in final production, which also uses labor. Other energy sources are important since natural gas prices have different drivers in the short and long run. In the short run, temperature, storage, and supply shortfalls are the main determinants, while long run determination is tied to other energy prices (Nick and Thoenes, 2014).

In our model, changes in the price of natural gas can have potentially different effects in the short and long run through several mechanisms. First, a reduction in the price of natural gas changes the cost structure of the LDC, which then reacts by modifying the tariff. Second, there is some degree of substitutability between raw capital and natural gas for capital service providers. Finally, we have some degree of substitution between types of capital services. The interactions between these mechanisms determine the aggregate effects of reductions in the relative price of natural gas.

Although this paper focuses on Brazil's natural gas market, our analysis and model might also be relevant to other countries. For example, Mexico's liberalization policies that started in the mid-1990s failed to increase competition and led to a lack of infrastructure upgrading (Duhalt, 2022). Another case is Algeria, the third largest OPEC country after Iran and Qatar, and a major supplier to Europe, with approximately 13% of the world's total exports of liquefied natural gas. In Algeria, all activities related to the natural gas market are carried out by two state-owned companies, Sonelgaz and Sonatrach (Layachi, 2013). Our framework can be useful for analyzing similar policies in such contexts.

Our paper is related to a large empirical literature identifying the effects of changes to the market structure of energy industries. Plane (1999), Andrés et al. (2006), Pombo and Taborda (2006), and Pérez-Reyes and Tovar (2009) all find that privatization and changes in ownership led to efficiency gains.[5] Eller et al. (2011) and Hartley and Medlock (2013) provide evidence that national oil companies tend to be less efficient than private oil companies. More closely related to our work, Rubaszek et al. (2021) estimate the effects of structural shocks on the dynamics of the U.S. natural gas market. They find that supply shocks induce a reduction in the spot price of natural gas of 3.3%, which is similar in magnitude to our experiment (5%), but they also found increases in natural gas production. Unlike them, we also find moderate GDP gains. We build on this literature and show the general equilibrium effects of increased competition in the short and long run on the natural gas market captured by reductions in the price of natural gas. We also evaluate how potential efficiency gains in natural gas can affect adoption and GDP.

We also build on the operations research literature on complementarity models applied to energy markets (Ruiz et al., 2014).[6] However, the main focus of this literature is on energy markets, without considering aggregate macroeconomic effects. One important aspect included in our model is investment adjustment costs, which are highlighted in the literature as important factors that determine supply conditions (Lise and Hobbs, 2008). We contribute to this literature by analyzing the macroeconomic effects of natural gas price reductions in a general equilibrium setting in which energy inputs have key central roles.

Another large strand of the literature has focused on the macroeconomic effects of oil price shocks in general equilibrium settings. In particular, Unalmis et al. (2009), Bodenstein and Guerrieri (2011), and Zhao et al. (2016) build open economy New Keynesian DSGE models where oil is used in production. In Alpanda and Peralta-Alva (2010), energy is also an input in production, with two technologies that differ in their energy intensity. Huynh (2016) incorporates endogenous energy production to investigate the differences in aggregate responses to energy price shocks from multiple sources. Balke and Brown (2018) build a neoclassical dynamic macroeconomic model with oil as an input to evaluate oil price shocks in the U.S. economy. We contribute to this literature by modeling energy from natural gas as relevant input and highlighting the role of LDCs in the natural gas chain. Furthermore, our framework explicitly includes two energy sources in the provision of capital services, placing their relative prices at the core of the short- and long-run macroeconomic effects in the presence of capacity constraints.

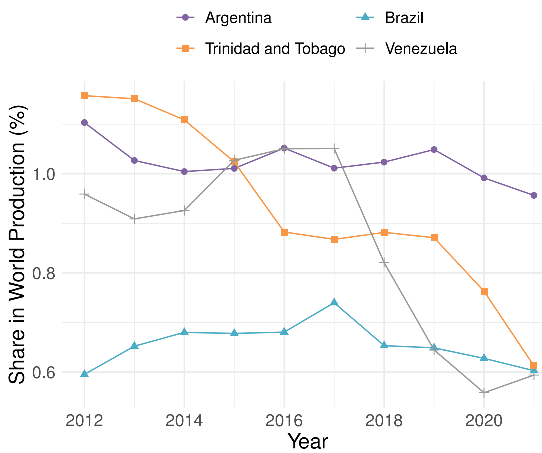
The paper proceeds as follows. Section 2 provides a background for the Brazilian natural gas sector. Section 3 presents the general equilibrium model for the LDC. Section 4 presents the data and the

[3] As highlighted in Melaina et al. (2013), the infrastructure used for liquefied natural gas (LNG) can be modified to handle a blend of hydrogen and natural gas, making it possible to gradually transition to hydrogen without incurring significant infrastructure costs.

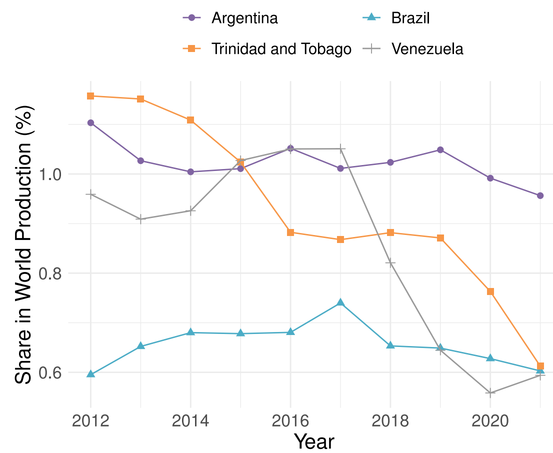
[4] Oliver (2019) shows that flexibility in the distribution of natural gas can increase the incentives for investments in distribution capacity.

[5] See Gakhar and Phukon (2018) for a review of the literature on the privatization of state-owned companies.

[6] Some examples include Lise and Hobbs (2008) and Lise and Hobbs (2009). They build a computational game theory model for the liberalization of the natural gas market in Europe. Another strand of the literature builds large-scale models for the natural gas markets (Egging, 2013; Huppmann, 2013; Huppmann and Egging, 2014). Dieckhöner et al. (2013) analyze the integration of the European natural gas markets. Devine et al. (2014) build a model for the U.K. natural gas market with stochastic demand as inputs. Egging and Holz (2016) use a large-scale global model to identify China's prominent role in global natural gas markets.



(a) Production



(b) Consumption

Fig. 1. Production and consumption of natural gas in Latin America.

calibration strategy. Section 5 discusses the main results and counterfactuals. In Section 6, we discuss the price elasticity of natural gas demand. Section 7 presents the policy implications of the natural gas reforms. Finally, Section 8 concludes.

2. The natural gas industry in Brazil

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

Even though the Brazilian Federal Constitution of 1988 established that the states were responsible for distribution activities, until 1995, the nationally owned Brazilian oil company Petrobras held a 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 have not necessarily achieved this goal.[7]

The gas market in Brazil is supplied by imports from Bolivia and Argentina, mainly through pipelines and by imports of liquefied natural gas from other locations. Over the last two decades, domestic production has more than tripled and currently represents 60% of the total supply, with 82% concentrated offshore (Diaz, 2021; Agência Nacional do Petróleo, 2022b). According to Agência Nacional do Petróleo (2022b), in June 2022, Petrobras was responsible for approximately 90% of domestic natural gas production. In 2020, Brazil was the third largest producer and the second largest consumer of natural gas in Latin America, with 24.2 billion cubic meters of production and 31.4 billion cubic meters of consumption (Agência Nacional do Petróleo, 2022a).

Using data from Agência Nacional do Petróleo (2022a), Figs. 1(a) and 1(b) show the shares in world production and consumption for the top four Latin American producers and consumers. Venezuela and Trinidad and Tobago decreased their shares, while Argentina and Brazil maintained roughly constant shares. This makes Brazil a key market for natural gas globally, so any changes in demand could have wide-reaching ramifications.

In terms of total domestic energy supply, natural gas in 2021 became the third most important source after petroleum and oil products, and sugarcane products (see Fig. 2(a)). Among fossil fuels, natural gas has largely replaced firewood and charcoal, as shown in Fig. 2(b).

Table 1
Dependency ratios (%).

	1975	1985	1995	2005	2015	2021
Coal	57.9	48.3	72.0	71.6	76.1	76.1
Electricity	0.1	1.0	11.4	8.8	5.6	3.4
Natural Gas	1.2	5.6	−1.7	42.5	41.4	40.5
Petroleum	79.8	43.1	49.0	0.6	−11.8	−42.2
Total	39.9	20.1	30.1	10.1	7.3	−3.7

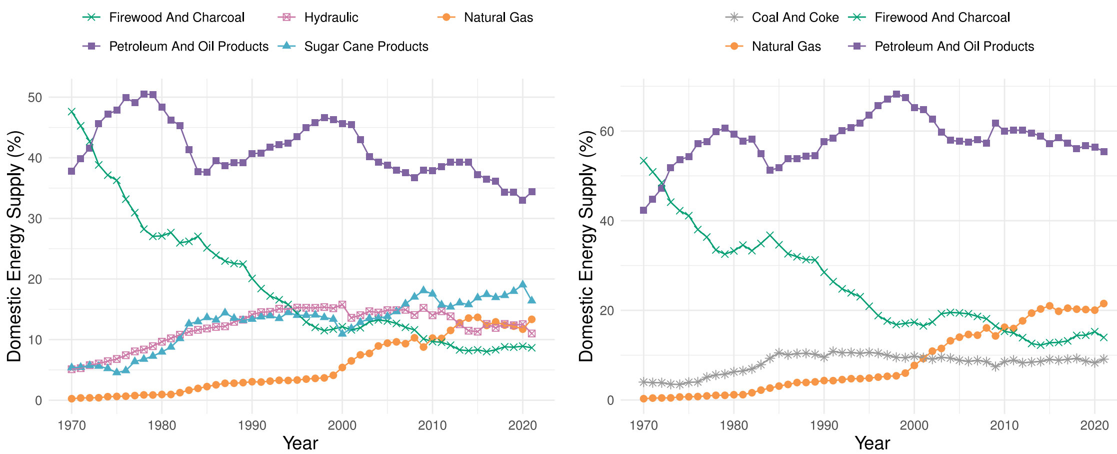
Table 2
Final consumption of natural gas by sector (% Final consumption).

	1975	1985	1995	2005	2015	2021
Final Non-Energy Consumption	22.2	37.3	21.6	5.6	3.8	1.4
Energy Sector	36.0	35.9	22.3	23.3	32.5	28.4
Residential	0.0	0.0	1.2	1.4	1.7	2.9
Commercial/Public	0.0	0.0	0.8	2.2	0.9	0.9
Transportation	0.0	0.0	1.1	12.9	8.7	12.0
Industrial	41.8	26.8	53.1	54.6	52.4	54.5

This rise in natural gas and other energy supplies has been insufficient for meeting the total demand. Table 1 shows data from Empresa de Pesquisa Energética (2022) for the dependency ratios of different energy sources. Dependency is defined as the difference between domestic energy demand and domestic production. The dependency ratio is defined as dependency divided by total domestic energy demand. Negative values indicate a net exporting position of the country, while positive values denote foreign dependency. Table 1 shows that natural gas dependency increased significantly from 1.2% in 1975 to 42.5% in 2005, and remained above 40% until 2021. However, on aggregate, the dependency ratio was negative in 2021 (−3.7%) due to the strong international position in petroleum exports.

Most of the demand in natural gas has been for final consumption (on average, 75%), of which 81% has been for final energy consumption. Table 2 shows the split of final energy consumption across sectors. Historically, the industrial sector has taken the lion's share of 44% on average and it has accounted for more than 50% of natural gas consumption since 1995. The second largest sector in natural gas consumption is the energy sector, which on average has accounted for 30.7% of natural gas consumption.

[7] A summary of the Brazilian natural gas industry, from a historical point of view, can be found in Junior and de Almeida (2007) and Diaz (2021).



(a) Over Total Energy Supply (b) Over Fossil Fuels

Fig. 2. Domestic energy supply.

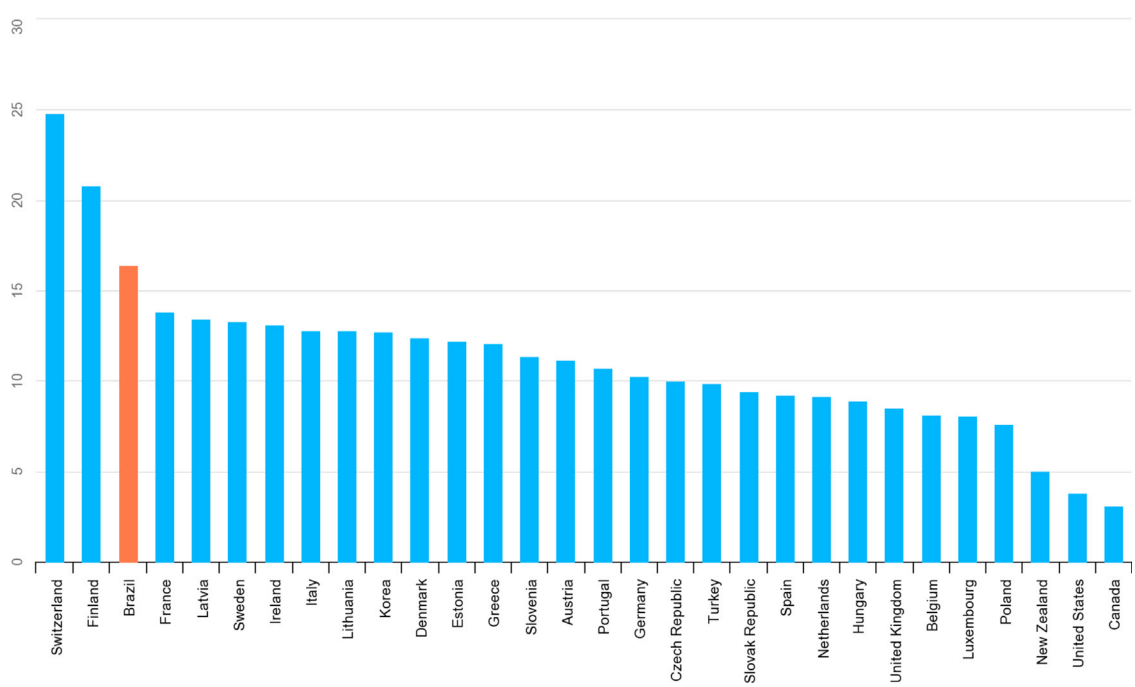


Fig. 3. Natural gas prices (USD/MBtu) for the industrial sector, 2019 (IEA, 2021).

Law 9.478 (Oil Law) passed in 1997 aimed to break the Petrobras' monopoly over the activities of research, exploration, production, and the refining of oil and natural gas. Eventually, even though other companies were allowed to participate in these activities, they were obliged to work alongside Petrobras, who held a stake in each step of every activity. Law 11.909 (Natural Gas Law) was introduced in 2009 and aimed more directly at the natural gas sector, abolishing the state monopoly. Even with the privatization of some companies, Petrobras continued to hold a stake in most of the LDCs. The exceptions were the LDCs from Rio de Janeiro and São Paulo, which had been privatized in 1998 and 1999, respectively.

In July 2019, Petrobras and the Brazilian competition authority (CADE) signed a Cessation Commitment Term (TCC). Both parties agreed that Petrobras would provide third-party access to infrastructure as a way to increase the number of players in gas commercialization and sell its transportation and distribution assets (Diaz, 2021). In line with the TCC, Petrobras sold 51% of Petrobras Gas S.A. (Gaspetro) to Compass Gás e Energia S.A. (Compass) in July 2022.

According to a statement from Petrobras, Gaspetro is a holding company with equity interests in 18 LDCs located in every region of Brazil. Its distribution networks add up to approximately 10 thousand km, serving more than 500 thousand customers, with a distributed volume of roughly 29 million m^3 per day.[8]

[8] Its corporate structure, which previously had Petrobras as the main shareholder with 51% of the shares, changed so that 51% of the shares now belong to Compass and 49% to Mitsui Gás e Energia do Brasil Ltda.

Fig. 3, obtained from IEA (2021), reports natural gas prices for the industrial sector in 2019, measured in USD/MBtu. Brazil ranks third in this selection of countries. IEA (2021) reports that natural gas prices have been consistently high in Brazil because sales contracts are linked to oil products. Thus, these prices do not necessarily reflect the fundamentals of the Brazilian gas market. Therefore, increased competition in the natural gas markets could drive prices downward and increase the adoption of natural gas.

3. Model

The following model describes a regional economy in which natural gas is distributed by a single monopolistic company facing a capacity constraint. Raw energy from different sources is supplied at a constant exogenous price, as in Díaz et al. (2004). Production uses labor and aggregate capital services. As in Atkeson and Kehoe (1999), capital services are provided by combining energy with raw capital. In the model, we differentiate between capital services from natural gas and those from other energy sources.

3.1. Energy production

The economy has two energy sources: natural gas and a composite of other sources, which we simply label *"other sources"*. In each period t, any amount of raw energy demanded from either source is supplied with exogenous prices π_t^g and π_t^e, respectively.[9] Raw energy must be distributed to the production sector to be usable. In the model, we assume that the LDC processes natural gas and distributes it to firms in the production sector, while we assume that other sources are directly converted with any amount of usable energy sold at tariff $p_t^e = \pi_t^e$.

3.2. Gas distribution

Natural gas distribution is carried out by a monopolistic company that decides in each period the tariff p_t^g charged for the gas distributed to the production sector, considering the corresponding demand curve $g(\cdot)$. 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, representing the extension of the distribution grid owned by the company. This capacity constraint can be increased or decreased in 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 of the company grid and π^G is the unit price of transforming investment into physical units of distribution grid pipelines into units of the final consumption good, assumed to be constant over time.

We assume that any investment in capacity that differs from the depreciated value $\delta^d G_t$ implies a quadratic adjustment cost given by $\frac{\pi^G \phi^d}{2}\left(\frac{I_t^d}{\pi^G G_t} - \delta^d\right)^2 G_t$. Adjustment costs capture the idea that grid maintenance is relatively straightforward, but expansions or quality improvements are costlier.[10]

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,[11] we can write its dynamic programming problem as follows:

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

subject to investment and capacity constraints

$$I_t^d = \pi^G\left[G_{t+1} - \left(1-\delta^d\right) G_t\right] \tag{2}$$

$$g_t\left(p_t^g\right) \leq G_t \tag{3}$$

The solution to the problem above is characterized by the monopolist's tariff-setting rule and the law of motion for G_t

$$p_t^g = \frac{\rho}{\rho-1}\left(\pi_t^g + z^d + \lambda_t\right) \tag{4}$$

$$1 + \phi^d\left(\frac{G_{t+1}}{G_t} - 1\right) = \Lambda_{t+1}\left\{\frac{\phi^d}{2}\left[\left(\frac{G_{t+2}}{G_{t+1}}\right)^2 - 1\right] + \left(1-\delta^d\right) + \frac{\lambda_{t+1}}{\pi^G}\right\} \tag{5}$$

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

Inspecting Eq. (5) shows that investments in the capacity of the LDCs are both backward and forward-looking. This implies that the current investment decision is affected both by the current state of the capacity and that of the future. Eq. (5), evaluated at the steady state, implies $\lambda_{ss} = \pi^G\left(r_{ss} + \delta^d\right)$. Since the Lagrange multiplier associated with the capacity constraint is positive, this means that the supply of natural gas must operate at full capacity. Substituting this into (4) shows that the tariff-setting rule considers the depreciation of the grid and the opportunity cost of investment captured by the interest rate.

3.3. Production sector

The production sector is composed of four different firms.[12] The first two firms provide capital services, but each firm uses a different energy source and type of capital. These two firms then sell capital services to a firm that aggregates the two types of capital services and sells them to the final good producer. The final good producer uses the aggregate capital services and labor to manufacture a final consumption good.[13] Fig. 4 illustrates the flow of quantities between these firms.

Capital services require powering capital with energy, and different energy sources power different types of capital. There is a single representative firm providing capital services for each type of energy source. The production of capital services powered with natural gas is described by a constant elasticity of substitution (CES) production function given by

$$s^g\left(k^g, g\right) = A^g\left[\alpha^g\left(k^g\right)^{\frac{\rho-1}{\rho}} + \left(1-\alpha^g\right)(g)^{\frac{\rho-1}{\rho}}\right]^{\frac{\rho}{\rho-1}} \tag{6}$$

where A^g is an efficiency parameter, g is the volume of natural gas, and k^g is the amount of rented capital that can be powered by natural gas.[14]

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

[10] Adjustment costs is a common setting in energy modeling. For example, see Huynh (2016).

[11] As it happens to energy prices, we 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.

[12] Since the profit maximization problem of all firms in the production sector in each period is time-independent, we drop the time index t in this subsection for readability.

[13] This setting is analogous to a single firm that aggregates all the inputs and produces the final consumption good. However, explicitly separating the sectors enables a more transparent analysis of how each input contributes to the overall production.

[14] The monopolistic distribution company will only set a finite price in an elastic point of the demand curve. Hence, it is required that $\rho > 1$. For the other firms, we assume a Cobb–Douglas production function, which allows us to easily match the shares of capital and energy in the data.

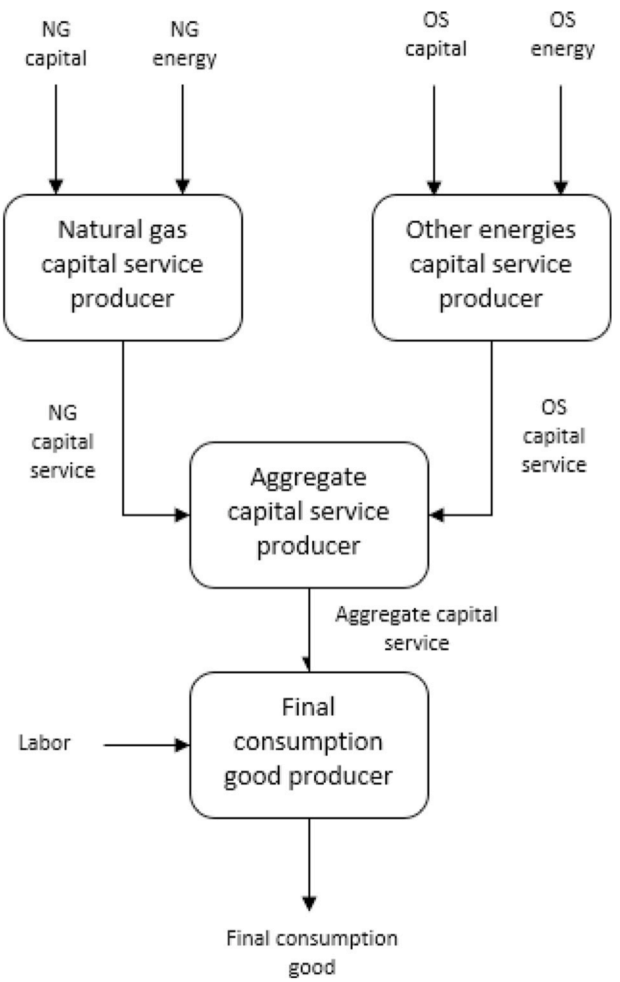


Fig. 4. Production sector flow.

We denote the rental rate for natural gas capital by r^g and the price of a unit of capital services powered by natural gas by q^g. Profit-maximizing conditions are

$$q^g A^g \alpha^g \left(\frac{s^g(k^g,g)}{A^g k^g}\right)^{\frac{1}{\rho}} = r^g \tag{7}$$

$$q^g A^g (1-\alpha^g) \left(\frac{s^g(k^g,g)}{A^g g}\right)^{\frac{1}{\rho}} = p^g \tag{8}$$

Capital services from other energy sources are produced according to the Cobb–Douglas technology (9)

$$s^e(k^e,e) = A^e (k^e)^{\alpha^e} (e)^{1-\alpha^e} \tag{9}$$

where A^e is a productivity parameter, e denotes the amount of energy, and k^e the amount of capital rented at a rate r^e. The price of these capital services is q^e and the profit-maximizing conditions are

$$q^e \alpha^e \frac{s^e(k^e,e)}{k^e} = r^e \tag{10}$$

$$q^e (1-\alpha^e) \frac{s^e(k^e,e)}{e} = p^e \tag{11}$$

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

$$s\left(s^g(k^g,g), s^e(k^e,e)\right) = \left[(s^g(k^g,g))^\gamma + (s^e(k^e,e))^\gamma\right]^{\frac{1}{\gamma}} \tag{12}$$

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

$$q\left(\frac{s}{s^g(k^g,g)}\right)^{1-\gamma} = q^g \tag{13}$$

$$q\left(\frac{s}{s^e(k^e,e)}\right)^{1-\gamma} = q^e \tag{14}$$

Finally, a representative firm uses aggregate capital services and labor to produce a final consumption good with the Cobb–Douglas technology

$$y(s,n) = A s^\alpha n^{1-\alpha} \tag{15}$$

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

$$\alpha \frac{y(s,n)}{s} = q \tag{16}$$

$$(1-\alpha)\frac{y(s,n)}{n} = w \tag{17}$$

3.4. Capital producer

Each type of capital (to be used with natural gas or with other sources) is produced by a representative firm that rents it to the firms in the production sector. We denote the depreciation rate for each type of capital as δ^i where $i \in \{g,e\}$. The production of new stock of capital is also subject to quadratic adjustment costs of $\frac{\phi^i}{2}\left(\frac{I^i_t}{k^i_t} - \delta^i\right)^2 k^i_t$ for $i \in \{g,e\}$. The producer of capital powered by energy of type $i \in \{g,e\}$ solves the dynamic problem

$$V^i_t\left(k^i_t\right) = \max_{I^i_t} r^i_t k^i_t - I^i_t - \frac{\phi^i}{2}\left(\frac{I^i_t}{k^i_t} - \delta^i\right)^2 k^i_t + \Lambda_{t+1} V^i_{t+1}\left(\left(1-\delta^i\right)k^i_t + I^i_t\right) \tag{18}$$

subject to

$$I^i_t = k^i_{t+1} - \left(1-\delta^i\right)k^i_t \tag{19}$$

The optimal path for capital powered by energy source i is characterized by the following dynamic equation

$$1 + \phi^i\left(\frac{k^i_{t+1}}{k^i_t} - 1\right) = \Lambda_{t+1}\left\{\frac{\phi^i}{2}\left[\left(\frac{k^i_{t+2}}{k^i_{t+1}}\right)^2 - 1\right] + \left(1-\delta^i\right) + r^i_{t+1}\right\} \tag{20}$$

3.5. Households

In this economy, there is a single representative agent that buys the final consumption good (c) and supplies labor (n) for which she receives a wage (w). The preferences of the household are described by a GHH (Greenwood et al., 1988) utility function and the agent solves the following problem[15]

$$\max_{c,n} c - \psi \frac{n^{1+\theta}}{1+\theta} \tag{21}$$

subject to the budget constraint

$$c = wn \tag{22}$$

which yields optimal labor supply and consumption conditions

$$n = \left(\frac{w}{\psi}\right)^{\frac{1}{\theta}} \tag{23}$$

$$c = w\left(\frac{w}{\psi}\right)^{\frac{1}{\theta}} \tag{24}$$

[15] Here, the use of the GHH utility function provides a closed-form solution for the labor supply and consumption demand.

3.6. Equilibrium

For each period $t \in \mathbb{N}$, given the exogenous interest rate, prices for raw energy inputs $\{r_t, \pi_t^g, \pi_t^e\}_{t=1}^{\infty}$, an 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 $(g_t, e_t, G_t, k_t^g, k_t^e, I_t^d, I_t^g, I_t^e, n_t, c_t, l_t)_{t=1}^{\infty}$ satisfying the following conditions:

1. $p_t^e = \pi_t^e$.
2. Given the demand curve $g(\cdot)$, $\{p_t^g, I_t^d, \lambda_{t+1}, G_{t+1}\}$ satisfy Eqs. (2) to (5).
3. Given the level of capital services powered by natural gas s_t^g and its price q_t^g, the demand curve that the monopolist faces, $g\left(p_t^g\right)$, satisfies Eq. (8), i.e., $g(p^g) = \frac{s^g}{A^g}\left(\frac{q_t^g A^g (1-\alpha^g)}{p_t^g}\right)^{\rho}$.
4. Given prices $\{r_t^g, p_t^g, q_t^g\}$, $\{k_t^g, g_t\}$ satisfy Eqs. (7) to (8).
5. Given prices $\{r_t^e, p_t^e, q_t^e\}$, $\{k_t^e, e_t\}$ satisfy Eqs. (10) to (11).
6. Given prices $\{q_t^g, q_t^e, q_t\}$, $\{s_t^g, s_t^e\}$ satisfy Eqs. (13) to (14).
7. Given prices $\{q_t, w_t\}$, $\{s_t, n_t\}$ satisfy Eqs. (16) to (17).
8. Given the rental rate r_t^i, $\left\{I_t^i, k_{t+1}^i\right\}$ satisfy Eqs. (19) and (20) for $i \in \{g, e\}$.
9. All markets clear.

4. Calibration — Taking the model to data

Before using the model for counterfactual analysis, we need to set values for the parameters. We use recent economic and energy consumption data for Brazil, at both national and state levels, as well as financial and operational information from the LDCs.

We select 12 of the major Brazilian natural gas LDCs for this study, considering their size and the availability of financial and operational information.[16] We use annual data for the period 2014 to 2019. We obtained most of the data from financial reports, with some data regarding volumes from the Brazilian Association of Piped Natural Gas Distribution Companies (Abegás). We chose this period because it represents an updated outlook of the LDCs analyzed but is sufficiently long to mitigate anomalous fluctuations due to extraordinary revenues and other unexpected events.

Most of the parameters have a direct counterpart in the data or have been estimated in other studies. However, others do not have this clear counterpart and must be jointly calibrated to match certain observed moments of the data. We calibrate the model in the steady state.

4.1. Externally calibrated parameters

The annual depreciation rates are from Souza Júnior and Cornelio (2020). We set the depreciation rate of the LDC pipelines δ^d to 0.0751, reported as the value for the petroleum and natural gas industry after 1973. As for the depreciation rate of both types of capital, δ^g and δ^e, we use the overall implicit depreciation value for capital of 0.066. The real interest rate r is set to 0.033. The value for capital services participation in total income α is 0.39, which equals the sum of capital services (0.35) and energy (0.04) participation in national income according to the Brazilian national accounts. We set α^e to 0.9, which is the capital participation in capital services from other energy sources. We calibrate θ by targeting the Frisch elasticity of labor supply estimated by Moura (2015) of 0.246.[17] The parameters for the quadratic adjustment cost functions, ϕ^d, ϕ^g and ϕ^e, are set to 0.15, which is within the range of values of the estimates by Pereira (2001) for Brazil. We assume these parameters are common across all regions and LDCs. Table 3 summarizes these values.

Table 3
Externally calibrated parameters.

Parameter	Value	Source
δ^d	0.075	Souza Júnior and Cornelio (2020)
δ^g	0.066	Souza Júnior and Cornelio (2020)
δ^e	0.066	Souza Júnior 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	0.150	Pereira (2001)
ϕ^g	0.150	Pereira (2001)
ϕ^e	0.150	Pereira (2001)

We calibrate other LDC-specific parameters using data from financial and operational reports. The relevant information is summarized in Table 4. The unitary cost of natural gas bought by the LDC (π^g in the model) is set to the average ratio between total expenditure on natural gas over the total volume of gas distributed. We calibrate the unit cost of distribution (z^d) as the average ratio of all costs, excluding gas expenditure, divided by total volume.

In order to obtain the volume of energy from other sources, we use the average share of natural gas energy in total energy consumption, taken from EPE (2020). The balance only shows aggregated data at the national level, so we assume the participation of natural gas in total energy is the same within all regions. Moreover, since energy from different sources might have different units, we convert them into volume of gas energy equivalents (in m^3). The cost of other energy sources (π^e) is computed as the energy sector's revenue minus the revenue from natural gas distribution divided by total energy minus natural gas energy.

There is a complex regulatory framework used to determine the tariffs that LDCs will charge to clients from different sectors and levels of natural gas consumption. Instead of introducing these complex tariff schemes, we target certain key moments with a direct counterpart in the model to match the average operational and financial statistics necessary for the model.

Evaluating Eq. (2) in the steady state and noting that in the steady state, the LDCs must operate at full capacity (i.e. $g_{ss} = G_{ss}$), we obtain $\pi^G = \frac{I_{ss}^d}{\delta^d g_{ss}}$. We use the average investment of each LDC (I_{ss}^d) and the average natural gas volume (g_{ss}) to calibrate an LDC-specific π^G. Table 5 summarizes the parameter values for each LDC.

4.2. Internally calibrated parameters

We still have seven parameters to calibrate that do not have a direct mapping to the data. Thus, we jointly calibrate them so that our model matches certain moments. Let $\mathbf{\Theta} = (A^g, A^e, A, \alpha^g, \gamma, \psi, \rho)^{\top}$ be the vector of parameters to be calibrated, $\mathbf{m}_d \in \mathbb{R}^6$ be a vector of moments obtained from the data, and $\mathbf{m}(\mathbf{\Theta})$ be the model's counterparts of these moments. The optimally calibrated parameter vector, $\mathbf{\Theta}^*$, is given by

$$\mathbf{\Theta}^* = \arg\min_{\Theta} \left[\mathbf{m}(\mathbf{\Theta}) - \mathbf{m}_d\right]^{\top} \mathbf{W} \left[\mathbf{m}(\mathbf{\Theta}) - \mathbf{m}_d\right] \tag{25}$$

Since all selected moments are positive, we minimize the sum of relative squared errors, meaning the weight matrix used is given by $\mathbf{W} = \text{diag}\left(1/\mathbf{m}_{d,i}^2\right)_{i=1}^{6}$. We target the following moments:

1. The 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.
2. Regional GDP, given by y_{ss} in the model.

[16] The list of selected companies is: Sulgás, SCGás, Compagás, Comgás, Gás Brasiliano, Naturgy São Paulo (formerly Gás Natural Fenosa), Naturgy Rio Capital (formerly CEG), Naturgy Rio Interior (formerly CEG-Rio), Gasmig, MSGás, Bahiagás, and Copergás.

[17] The Frisch elasticity of labor supply in the model is equal to $1/\theta$.

Table 4
Annual average operational and financial statistics.

LDC	Gross revenue (million R$)	Natural gas purchase (million R$)	Net profit (million R$)	Investment (million R$)	Natural gas volume (million m^3)
Sulgás	896	601	80	26	717
SCGás	904	564	29	31	631
Compagás	777	467	62	36	467
Comgás	8614	3575	926	468	4917
Gás 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
MSGás	375	286	17	18	639
Bahiagás	2017	1368	128	41	1360
Copergás	1238	830	92	30	1554

Table 5
Steady state calibration — LDC-specific.

LDC	Parameter			
	π^g	π^e	z^d	π^G
Sulgás	0.0011	0.0083	0.0004	0.000049
SCGás	0.0020	0.0092	0.0010	0.000110
Compagás	0.0014	0.0128	0.0006	0.000104
Comgás	0.0002	0.0012	0.0002	0.000031
Gás Brasiliano	0.0057	0.0209	0.0032	0.000443
Naturgy São Paulo	0.0039	0.0139	0.0022	0.000344
Naturgy Rio Capital	0.0012	0.0016	0.0007	0.000073
Naturgy Rio Interior	0.0018	0.0018	0.0004	0.000037
Gasmig	0.0012	0.0046	0.0004	0.000040
MSGás	0.0028	0.0091	0.0005	0.000170
Bahiagás	0.0021	0.0040	0.0008	0.000065
Copergás	0.0020	0.0035	0.0007	0.000070

3. The 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.
4. 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.
5. The ratio of natural gas capital services to other energy sources capital services, i.e., s^g_{ss}/s^e_{ss}.
6. Total labor, given by n_{ss} in the model.
7. Price elasticity of demand in the data.

Regional GDP is taken from the regional accounts published by the Brazilian Statistical Office (IBGE), which reports the GDP for each state. We use the average value between 2014–2018. Most LDCs in this study are the only ones in their state, so state GDP is used. However, the São Paulo and Rio de Janeiro states have multiple companies. In those cases, we divide state GDP proportionally according to their revenue. We scale all monetary values by the GDP and set the GDP target to 1. The natural gas efficiency relative to other energy sources is taken from the Energy Information System of the Ministry of Mines and Energy (SIE Brasil - MME). The most recent values are from 2004. Efficiency here is in the physical sense, that is, the share of energy that is transformed into effective work. Labor is set to 44/168, the average working week time. Table 17 contains the values for each target.

The elasticity of substitution ρ and the price elasticity of demand require some consideration. The price elasticity of natural gas demand is crucial for gauging the impact of a reduction in the price of natural gas. In the model, it depends crucially on the value of ρ, since the demand for natural gas is given by

$$g = \left(\frac{1-\alpha^g}{p^g}\right)^{\rho} \frac{\mathbb{M}}{(1-\alpha^g)^{\rho}(p^g)^{1-\rho} + (\alpha^g)^{\rho}(r^g)^{1-\rho}}$$

where $\mathbb{M} = r^g k^g + p^g g$ is the total expenditure on inputs. We can define the price elasticity of demand as

$$\varepsilon^D_{p^g} \equiv \frac{d\log(g)}{d\log(p^g)} = -\rho + (\rho-1)\frac{(1-\alpha^g)^{\rho}(p^g)^{1-\rho}}{(1-\alpha^g)^{\rho}(p^g)^{1-\rho} + (\alpha^g)^{\rho}(r^g)^{1-\rho}} \quad (26)$$

which depends on ρ, the price of natural gas, and the rental rate of natural gas-powered capital.

There are several studies estimating this elasticity for different countries. However, there is no consensus on its value, since it depends on various factors such as the stage of development (see Shahbaz et al., 2014), the sector (residential or industrial), the country, the time horizon (long or short run), or the model specification. In particular, Shahbaz et al. (2019) show that education and export diversification negatively affect the demand for energy, whereas economic growth increases it. Most estimates do not focus on the price elasticity of natural gas demand per se but rather on energy demand in a more general sense.

Labandeira et al. (2017) perform a meta-analysis on the price elasticity of energy demand, and they find the long-run elasticity is in the range $[-1.16, -0.31]$. Burke and Yang (2016) estimate the price and income elasticities of natural gas demand using data from multiple countries, including Brazil. They estimate the long-run price elasticity of natural gas demand to be around -1.25. Burke and Abayasekara (2018) document that the U.S. industrial sector has a long-run demand elasticity for electricity in the range $[-1.44, -1.34]$, and they also estimate the demand-price elasticity for electricity of all economic sectors as being -1.0. Huntington et al. (2019) review the estimates for energy demand focused on lower-income countries, including Brazil. They report that the long-run price elasticity of natural gas demand for developing countries is -1.36, similar to the one estimated for the industrial sector in OECD countries (-1.35). Thus, we choose as a target the value -1.25, estimated by Burke and Yang (2016). It implies $\rho > 1$ (which is necessary for our monopolist to set a finite price) and is a conservative estimate given the evidence for developing countries discussed previously.

While all parameters are jointly determined, the productivity term A is determined mostly by regional GDP. The ratio of natural gas capital services to capital services from other energy sources allows us to pin down the elasticity γ.[18] Note that both α^g and A^g depend on the capital income share within natural gas capital services and ρ.[19] Since the capital income share for other energies is equal to α^e, moment 3 helps us match α^g given the elasticity. As for the productivity term A^g, it is identified by the relative efficiency of natural gas capital services

[18] This can be seen from the ratio of Eqs. (13) to (14).

[19] See Cantore and Levine (2012) for how to deal with dimensional constants in economic models.

Table 6
Internally calibrated parameters.

LDC	Parameter						
	A^g	A^e	A	α^g	γ	ψ	ρ
Sulgás	189	238	0.159	0.941	0.864	537	1.265
SCGás	1051	1677	0.072	0.915	0.696	539	1.270
Compagás	173	215	0.169	0.942	0.891	537	1.263
Comgás	194	277	0.134	0.927	0.724	539	1.278
Gás Brasiliano	306	485	0.120	0.877	0.675	539	1.276
Naturgy São Paulo	2520	3692	0.054	0.876	0.720	539	1.279
Naturgy Rio Capital	25	89	0.041	0.902	0.122	539	1.279
Naturgy Rio Interior	35	133	0.016	0.898	0.089	539	1.279
Gasmig	155	210	0.160	0.911	0.780	539	1.276
MSGás	236	300	0.144	0.892	0.820	539	1.278
Bahiagás	10555	18789	0.026	0.872	0.578	539	1.289
Copergás	68127	99795	0.014	0.853	0.703	539	1.302

Table 7
Relative deviation for each moment.

LDC	Model relative deviation from data moments (%)						
	Price Elasticity	NG share	GDP	Capital income	NG rel. eff.	Labor	Relative capital services
Sulgás	−0.042	0.001	−0.014	1.013	−0.011	0.071	−0.009
SCGás	−0.049	0.003	−0.000	0.754	−0.011	0.002	−0.007
Compagás	−0.038	0.000	−0.020	1.093	−0.011	0.101	−0.010
Comgás	−0.011	0.001	−0.000	0.106	−0.002	0.001	−0.001
Gás Brasiliano	−0.020	0.002	−0.000	0.264	−0.004	0.002	−0.002
Naturgy São Paulo	0.001	0.000	0.000	−0.007	0.000	0.000	0.000
Naturgy Rio Capital	0.001	−0.000	−0.000	−0.005	0.000	0.000	0.000
Naturgy Rio Interior	0.002	−0.000	−0.000	−0.007	0.000	0.000	0.000
Gasmig	−0.017	0.002	−0.001	0.223	−0.004	0.007	−0.002
MSGás	−0.003	0.000	0.000	0.043	−0.001	0.000	−0.000
Bahiagás	0.109	−0.012	0.000	−0.842	0.020	0.000	0.006
Copergás	0.212	−0.028	−0.000	−1.560	0.038	0.000	0.006

(moment 4).[20] Finally, the share of natural gas energy in total energy consumption helps pin down A^e.

Table 6 shows the calibrated values for each parameter and company. Most values are relatively stable across the companies, except for the productivity parameters A^g and A^e, which present larger heterogeneity. The distribution parameter α^g is found to be large and above 0.8 in all cases. The elasticity of substitution between capital services powered by different energy sources is controlled by γ and, in all cases, γ is positive. This implies that capital services powered by different energy sources are gross substitutes, which is consistent with the empirical literature (Brown and Yücel, 2008).[21] The elasticity of substitution between raw capital and natural gas ρ shows relatively stable values across LDCs around 1.27. The model fits the data very closely, where the largest deviation is −1.56% in capital income. Table 7 summarizes the calibration errors.

5. Experiments

We perform some counterfactual exercises in order to investigate how an increase in competition within the natural gas production sector would affect LDCs and regional economies. We use the model to simulate a change in the price of natural gas π_t^g. For each LDC, we consider three scenarios: (i) where only the natural gas price is reduced; (ii) where the price of both types of energy changes (π_t^g and π_t^e); and (iii) where π_t^g is reduced by 5% but π_t^e is reduced so that the long-run share of natural gas remains constant.

In addition to price changes, we examine the potential impact of an increase in the relative efficiency of natural gas as a provider of capital services. The analysis of this counterfactual scenario serves two purposes. First, it allows us to gauge aggregate gains from potential innovations due to increased competition. Second, it is useful to assess the use of natural gas as a transition fuel; thus, increasing its relative efficiency could be a channel for energy transitions. We simulate the model for 100 periods, enough for the model to transition from one steady state to another.

5.1. Decline in the price of natural gas

The main Brazilian natural gas producer (Petrobras) has an average profit margin of approximately 10% in its natural gas operations. We assume that this margin is reduced by half through a reduction in the price charged to LDCs. This reduction in the profit margin is equivalent to a 5% reduction in the price of natural gas, holding costs constant. The model starts at a steady state in period zero and becomes aware of future changes in price in the next period, with no unforeseen shocks afterward. All other parameters and prices of other energy sources are kept constant.

All LDCs are characterized by a common pattern. First, a quick transition that takes only a few years is driven by the expansion of pipelines. Then, a relatively slower transition driven by changes in both capital stocks takes several decades to reach a steady state. These patterns are shown in Appendix C.

Table 8 reports the short and long-run impacts of price reduction by LDC. In the long run, all LDCs reduce their tariffs, and this reductions range from 2.5% to 4.2%. This implies that a reduction in price is not fully absorbed by a reduction in the tariff. In order to understand this result, note that from Eq. (4), we can compute the elasticity of the tariff with respect to the price of natural gas. In particular, this is given by

$$\frac{d\log(p^g)}{d\log(\pi^g)} = \frac{\pi^g}{\pi^g + z^d + \lambda}$$

[20] Manipulating Eqs. (8) and (11) we can show

$$\frac{s_{ss}^g/g_s s}{s_{ss}^e/e_{ss}} \propto (A^g)^{1-\rho}.$$

[21] The limiting case of $\gamma = 1$ in Eq. (12) implies an infinite elasticity of substitution, which is the case of perfect substitutes.

Table 8
Impact of a 5% Natural Gas Cost Reduction by LDC.

LDC	Short run % changes				Long run % changes			
	Tariff	Volume	Revenue	Profit	Tariff	Volume	Revenue	Profit
Sulgás	−3.7	5.3	1.4	1.4	−3.8	6.2	2.2	2.2
SCGás	−3.3	4.6	1.2	1.2	−3.3	4.8	1.4	1.4
Compagás	−3.3	4.7	1.2	1.3	−3.4	5.7	2.1	2.1
Comgás	−2.4	3.4	0.9	1.0	−2.5	3.7	1.2	1.2
Gás Brasiliano	−3.1	4.4	1.2	1.2	−3.2	4.7	1.4	1.4
Naturgy São Paulo	−3.1	4.5	1.2	1.3	−3.2	4.9	1.5	1.6
Naturgy Rio Capital	−3.1	4.2	0.9	0.9	−3.2	4.3	1.0	1.0
Naturgy Rio Interior	−4.1	5.5	1.2	1.2	−4.1	5.6	1.2	1.2
Gasmig	−3.7	5.3	1.5	1.5	−3.7	5.9	2.0	2.0
MSGás	−4.1	6.2	1.8	1.9	−4.2	7.3	2.8	2.8
Bahiagás	−3.7	5.3	1.4	1.4	−3.7	5.5	1.6	1.6
Copergás	−3.7	5.6	1.8	1.8	−3.7	6.1	2.2	2.2

Table 9
Impact of a 5% natural gas cost reduction on the energy share.

LDC	NG energy share (%)		
	Current	Short run (after 1 year)	Long run
Sulgás	13.1	13.7	13.8
SCGás	13.1	13.6	13.7
Compagás	13.1	13.7	13.8
Comgás	13.1	13.5	13.5
Gás Brasiliano	13.1	13.6	13.7
Naturgy São Paulo	13.1	13.6	13.7
Naturgy Rio Capital	13.1	13.6	13.6
Naturgy Rio Interior	13.1	13.7	13.7
Gasmig	13.1	13.7	13.8
MSGás	13.1	13.8	14.0
Bahiagás	13.1	13.7	13.7
Copergás	13.1	13.8	13.8

Thus, the reduction in the price of natural gas (π^g) is compensated by the distribution cost (z^d) and the investment shadow cost (λ) that remain constant.[22]

Besides tariff reductions, all LDCs increase their activity. Volumes of natural gas sold, revenues, and profits all increase. The volume of natural gas sold increases significantly, with short-term increases ranging from 3.4% to 6.2% and long-term increases reaching up to 7.3%. Revenues and profits have similar increases but are smaller in magnitude than volume changes. The maximum profit increase is 2.8% for MSGás in the long run. Comparing short and long-run effects in Table 8 shows that a significant proportion of the long-run effects occur in the first years. Transition plots for these variables over the years for each LDC can be found in Appendix C.

The impact of each regional economy's natural gas participation on energy consumption, which was initially 13.1% for all regional economies, increases in all cases, both in the short and the long run. Table 9 shows both the short- and long-run participation of natural gas, considering the short term to be the following year after the occurrence of the price shock. A significant part of the increase in participation occurs in the short run, meaning there is a quick expansion in distribution capacity. The rest of the expansion occurs at a much slower pace, taking decades to reach a steady state. This is because capital producers take much longer to replace capital powered by other energy sources with natural gas.

Table 10 shows the aggregate effects on the local economy. GDP increases in the short-run with a median value of 0.05% across regions and a maximum of 0.13% for Naturgy Rio Interior. In the long run, the median increase is 0.06%. This increase in long-run GDP is explained by larger increases in natural gas capital stock than the reductions in capital powered by other energy sources.

Two opposing forces can explain the overall long-run effects on capital stocks from different sources. First, as natural gas becomes cheaper relative to the rental rate of capital, the capital service producer demands less capital in favor of more gas. The second effect comes from the aggregation of both types of capital services. Since capital services powered by natural gas have become cheaper, there is an increase in the demand for this type of capital service. As γ approaches 1, the substitution between the two types of capital services becomes stronger. In fact, for the two companies with the lowest value of γ, i.e., Naturgy Rio Capital and Naturgy Rio Interior, both types of capital increase in the short and the long run.

Rubaszek et al. (2021) study through the lens of a Bayesian structural vector autoregression model the impact of structural shocks to the dynamics of the U.S. natural gas market. They find that a positive supply shock leads to increased production (1.7%) and reduced spot prices (3.3%) in the short-run. Over the longer run, they find further reductions in price and increases in production. We simulate a reduction of 5% which is similar in magnitude to the effect they find. We find, however, larger increases in volume and a reduction in tariffs. Although Rubaszek et al. (2021) find that there is an insignificant response in economic activity, we find moderate GDP gains.

5.2. Decline in all energy prices with constant shares

One of the main conclusions from the previous experiment is that natural gas consumption is elastic to price changes. For example, a small reduction of 5% in price caused long-run volume changes up to 7.3%. The main reason for this is the high substitutability between the different capital services, which is realistic since capital services are expected to be similar, regardless of the energy source that powers them.

In the previous counterfactual, we kept prices for other energy sources constant to understand the mechanisms at play in the model. However, it is realistic to expect that other energy prices would drop in response to the drop in natural gas prices due to competition between energy sources. Thus, we simulate another experiment in which both prices fall.[23] However, in order to discipline this change, we reduce the price of other energies up to the point where the share of natural gas participation in total energy remains constant in the long run and keep the fall in natural gas price at 5%. These reductions range between 2.92% and 5.08%. Table 11 shows the price reduction for each regional economy.

Table 12 shows the short- and long-run impacts for all LDCs. 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 Eqs. (4) and (5). The volume of gas

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

[23] 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.

Table 10
Impact of a 5% natural gas cost reduction by regional economy.

LDC	Short run % changes			Long run % changes		
	GDP	Capital (NG)	Capital (OS)	GDP	Capital (NG)	Capital (OS)
Sulgás	0.03	0.20	−0.04	0.03	1.12	−0.24
SCGás	0.04	0.11	−0.02	0.05	0.43	−0.09
Compagás	0.02	0.19	−0.04	0.03	1.18	−0.25
Comgás	0.04	0.12	−0.02	0.05	0.48	−0.11
Gás Brasiliano	0.05	0.13	−0.02	0.06	0.46	−0.10
Naturgy São Paulo	0.05	0.16	−0.03	0.06	0.64	−0.14
Naturgy Rio Capital	0.10	0.02	0.03	0.12	0.05	0.10
Naturgy Rio Interior	0.13	0.02	0.05	0.16	0.06	0.14
Gasmig	0.05	0.22	−0.04	0.06	0.96	−0.21
MSGás	0.06	0.33	−0.07	0.07	1.55	−0.34
Bahiagás	0.09	0.14	−0.02	0.11	0.46	−0.08
Copergás	0.10	0.28	−0.06	0.12	1.05	−0.23

Table 11
Price reduction in other energy sources — Constant energy shares.

LDC	% Drop in OS price
Sulgás	3.69
SCGás	3.82
Compagás	3.09
Comgás	2.92
Gás Brasiliano	3.78
Naturgy São Paulo	3.79
Naturgy Rio Capital	3.95
Naturgy Rio Interior	5.08
Gasmig	4.27
MSGás	4.86
Bahiagás	4.60
Copergás	4.85

sold, revenues, and profits all increase but the magnitudes are smaller now both in the short and the long run compared to the previous counterfactual. Note further that long-run changes in revenues and profits are smaller than in the short run. This is because since all energy prices fall, the demand for both types of capital services increases, and the LDCs can increase profits in the short run. However, these effects are damped as capital composition changes in the long run.

Since the price of other energies also dropped, and they have larger participation, the impact on the regional economy is now larger. Increases in GDP went as high as 0.43% for Copergás in the long run, as shown in Table 13. The drop in other energy sources' prices quickly affects the production sector, generating a larger impact on GDP in the short run.

As for capital, there is a mild reduction in natural gas capital for some companies in the long run. Given that the long-run participation of other energy sources must be constant and that it is larger than the participation of natural gas, the increase in the demand for capital services powered from other sources is larger than the increase in the demand for natural gas capital services. In companies with a larger substitution between types of capital services (i.e., larger γ) this effect reduces natural gas-powered capital. Nevertheless, for most companies, there is an increase in both types of capital.

5.3. Uniform decline in all energy prices

In a third counterfactual, instead of keeping long-term energy shares constant, we now assume that all energy prices fall uniformly by 5%. In this case, short-term responses are similar to those in the previous experiment. Volume increases between 3.1% and 5.7%, while revenues and profits increase between 0.5% and 1.5%. However, some LDCs present revenues and profits reductions in the long run. Table 14 summarizes the impacts by LDCs.

For most LDCs, there are mild increases in revenues and profits in the long run, with all of them increasing volumes. However, Compagás and Sulgás experience a 1.1% and 0.3% reduction in profits, respectively. From Table 11, we can see that both Sulgás and Compagás have relatively small reductions in the price of other energies compared to other LDCs. This suggests that these companies are more sensitive to competition. The reason why Comgás does not experience a reduction in profits and revenues is that the 5% decline in the price of natural gas induces a smaller reduction in the tariff (−2.5% versus −3.4% and −3.8% for Compagás and Sulgás, respectively); this allows Comgás to keep higher revenues and profits. However, this turns into a more significant reduction of the natural gas share in the long run, as shown in Table 15.

Table 16 shows the effects on GDP and capital for each LDC. In terms of changes in GDP, we find increases in the short-run that range from 0.27% to 0.33%, and in the long run, from 0.36% up to 0.44%. As in the previous experiment, we find reductions in the natural gas capital stock for some LDCs, but they all increase the capital stock in other energy sources. These declines can be explained by substitution between types of capital services. Indeed, the natural gas share for some companies declines substantially, and the increase in aggregate demand for capital services is satisfied with capital from other sources.

5.4. An increase in the relative efficiency of natural gas

We now turn to the question of inducing transitions from other energies toward natural gas. IEA (2022) has emphasized the significance of natural gas as a transition fuel toward cleaner energy sources. The report emphasizes that the existing infrastructure can be adapted for other types of cleaner liquid gases, thus providing a cost effective and sustainable solution for future energy needs. One of the key messages of the literature on directed technical change (Acemoglu, 1998) and the environment is that innovation is key for energy transitions.[24] In particular, Fried (2018) has shown that research efforts can be directed to increase the efficiency of cleaner inputs through a carbon tax. In light of these results, we assess the effects of an increase in the relative efficiency of natural gas in providing capital services.

Our calibration implies that the provision of natural gas capital services heavily relies on raw capital by the value of α^g. This parameter can be thought of as the relative efficiency of raw capital relative to natural gas. To see this, suppose we replaced the production function of capital service providers (6) as

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

[24] See Hémous and Olsen (2021) for a review of the literature on directed technical change and environmental economics.

Table 12
Impact of a reduction in energy prices by LDC — Constant long run shares.

LDC	Short run % changes				Long run % changes			
	Tariff	Volume	Revenue	Profit	Tariff	Volume	Revenue	Profit
Sulgás	−3.7	4.9	0.9	0.9	−3.8	4.3	0.4	0.4
SCGás	−3.3	4.4	1.0	1.0	−3.3	4.4	0.9	0.9
Compagás	−3.3	4.3	0.8	0.8	−3.4	3.7	0.1	0.1
Comgás	−2.4	3.2	0.8	0.8	−2.5	3.3	0.7	0.7
Gás Brasiliano	−3.1	4.2	1.0	1.0	−3.2	4.3	1.0	1.0
Naturgy São Paulo	−3.1	4.2	1.0	1.0	−3.2	4.3	1.0	1.0
Naturgy Rio Capital	−3.1	4.3	1.0	1.1	−3.2	4.4	1.1	1.1
Naturgy Rio Interior	−4.1	5.7	1.4	1.4	−4.1	5.8	1.4	1.4
Gasmig	−3.7	5.0	1.1	1.2	−3.7	4.9	1.0	1.0
MSGás	−4.1	5.6	1.3	1.4	−4.2	5.6	1.2	1.2
Bahiagás	−3.7	5.2	1.3	1.3	−3.7	5.2	1.4	1.4
Copergás	−3.7	5.3	1.5	1.5	−3.7	5.5	1.6	1.6

Table 13
Impact of a reduction in energy prices by regional economy — Constant long run shares.

LDC	Short run % changes			Long run % changes		
	GDP	Capital (NG)	Capital (OS)	GDP	Capital (NG)	Capital (OS)
Sulgás	0.21	−0.07	0.13	0.29	−0.64	0.49
SCGás	0.22	0.01	0.12	0.30	−0.03	0.38
Compagás	0.18	−0.09	0.12	0.24	−0.78	0.46
Comgás	0.17	0.03	0.09	0.24	0.05	0.27
Gás Brasiliano	0.22	0.04	0.11	0.30	0.07	0.35
Naturgy São Paulo	0.23	0.04	0.11	0.31	0.09	0.35
Naturgy Rio Capital	0.23	0.07	0.11	0.31	0.21	0.31
Naturgy Rio Interior	0.30	0.08	0.14	0.40	0.27	0.40
Gasmig	0.26	0.03	0.13	0.35	−0.02	0.42
MSGás	0.30	0.04	0.15	0.40	−0.01	0.48
Bahiagás	0.30	0.09	0.13	0.39	0.26	0.39
Copergás	0.33	0.14	0.13	0.43	0.43	0.38

Table 14
Impact of a reduction in energy prices by LDC — Uniform decline.

LDC	Short run % changes				Long run % changes			
	Tariff	Volume	Revenue	Profit	Tariff	Volume	Revenue	Profit
Sulgás	−3.7	4.7	0.8	0.8	−3.8	3.7	−0.3	−0.3
SCGás	−3.3	4.3	0.9	0.9	−3.3	4.2	0.7	0.7
Compagás	−3.3	4.0	0.5	0.5	−3.4	2.4	−1.1	−1.1
Comgás	−2.4	3.1	0.6	0.7	−2.5	3.0	0.4	0.4
Gás Brasiliano	−3.1	4.2	0.9	0.9	−3.2	4.2	0.8	0.8
Naturgy São Paulo	−3.1	4.2	0.9	1.0	−3.2	4.1	0.8	0.8
Naturgy Rio Capital	−3.1	4.3	1.1	1.1	−3.2	4.5	1.2	1.2
Naturgy Rio Interior	−4.1	5.7	1.4	1.4	−4.1	5.8	1.4	1.4
Gasmig	−3.7	4.9	1.1	1.1	−3.7	4.7	0.9	0.9
MSGás	−4.1	5.6	1.3	1.3	−4.2	5.6	1.1	1.1
Bahiagás	−3.7	5.1	1.3	1.3	−3.7	5.2	1.3	1.3
Copergás	−3.7	5.3	1.5	1.5	−3.7	5.5	1.6	1.6

Table 15
Impact of a reduction in energy prices on the energy share.

LDC	NG energy share (%)		
	Current	Short run (after 1 year)	Long run
Sulgás	13.1	13.0	12.9
SCGás	13.1	13.0	12.9
Compagás	13.1	12.9	12.7
Comgás	13.1	12.8	12.8
Gás Brasiliano	13.1	13.0	12.9
Naturgy São Paulo	13.1	13.0	12.9
Naturgy Rio Capital	13.1	13.0	13.0
Naturgy Rio Interior	13.1	13.1	13.1
Gasmig	13.1	13.0	13.0
MSGás	13.1	13.1	13.1
Bahiagás	13.1	13.1	13.1
Copergás	13.1	13.1	13.1

Table 16
Impact of a reduction in energy prices by regional economy — uniform decline.

LDC	Short run % changes			Long run % changes		
	GDP	Capital (NG)	Capital (OS)	GDP	Capital (NG)	Capital (OS)
Sulgás	0.28	−0.18	0.20	0.38	−1.27	0.76
SCGás	0.28	−0.02	0.17	0.37	−0.18	0.53
Compagás	0.27	−0.27	0.21	0.38	−2.02	0.91
Comgás	0.28	−0.04	0.17	0.37	−0.27	0.55
Gás Brasiliano	0.28	0.01	0.16	0.38	−0.06	0.50
Naturgy São Paulo	0.29	0.01	0.16	0.39	−0.09	0.51
Naturgy Rio Capital	0.27	0.08	0.13	0.36	0.25	0.37
Naturgy Rio Interior	0.30	0.08	0.14	0.39	0.26	0.40
Gasmig	0.29	−0.00	0.16	0.40	−0.19	0.53
MSGás	0.30	0.04	0.15	0.41	−0.05	0.50
Bahiagás	0.31	0.08	0.14	0.42	0.24	0.43
Copergás	0.33	0.14	0.13	0.44	0.41	0.40

where Γ^k and Γ^g denote capital augmenting and natural gas augmenting efficiency, respectively. It can be shown that

$$\alpha^g \equiv \frac{\tilde{\alpha}^g \left(\Gamma^k\right)^{\frac{\rho-1}{\rho}}}{\tilde{\alpha}^g \left(\Gamma^k\right)^{\frac{\rho-1}{\rho}} + (1-\tilde{\alpha}^g)\left(\Gamma^g\right)^{\frac{\rho-1}{\rho}}}$$

$$\text{and} \quad A^g \equiv \left(\tilde{\alpha}^g \left(\Gamma^k\right)^{\frac{\rho-1}{\rho}} + (1-\tilde{\alpha}^g)\left(\Gamma^g\right)^{\frac{\rho-1}{\rho}}\right)$$

therefore, we can think of a reduction in α^g as an increase in Γ^g relative to Γ^k.[25]

In this experiment, we reduce α^g from 1% to 3% and report its effects in the long run on GDP, on the volume of natural gas, and on the two types of raw capital. Fig. 5 reports these results. The highlighted line with circles denotes the average effect across LDCs, while each line with squares reports individual LDC effects. We first find that there are moderate average GDP gains, significant increases in the share of natural gas, a reduction in capital from natural gas, and a heterogeneous response of capital in other energies that on average is slightly negative. Regarding average responses, GDP gains range from 0.02% to 0.13% if natural gas efficiency increases by 1% or 3%, respectively. The average natural gas share increases between 1.4 and 4.4 percentage points to increases of 1% and 3%, respectively.

The reduction in natural gas capital can be explained by the fact that increases in the efficiency of natural gas in the provision of capital services imply a substitution of raw capital for more natural gas. This increases the volume of natural gas.[26] This experiment highlights how increasing natural gas efficiency can result in an economy more intensive in natural gas. Nevertheless, this experiment also highlights significant heterogeneity across LDCs in GDP gains and changes in the capital stock powered by other energies. Despite these differences, the shares of natural gas increase in all cases.

6. On the price elasticity of demand

As discussed in Section 4.2, the price elasticity of natural gas demand is an important parameter. In this section, we test the sensitivity of the model to changes in the elasticity of substitution ρ. We recalibrate the model keeping all targets as before except for the price elasticity of demand, which we set to −1.44 and −1.1. We take these values based on the empirical estimates discussed in Section 4.2. For these two calibrations, we perform the counterfactual of improved efficiency in natural gas by reducing α^g between 1% and 3%. Fig. 6 shows the effects on GDP for these two elasticity values.

In both scenarios, the effects on GDP are heterogeneous across regions. However, in the least elastic case, the average GDP change across LDCs is slightly negative and relatively constant. On the other hand, in the more elastic case, it is positive and increasing. This is because the negative impacts are larger in the least elastic case, and the gains are smaller relative to the more elastic case. This shows that aggregate gains will crucially depend on the value of the elasticity of substitution.

We compare the average effects across these two calibrations with the benchmark calibration. We plot the average percent change in GDP across LDCs for the three elasticity values and the natural gas share. In Fig. 7(a), we show average changes in GDP across the three calibrations. Relative to the benchmark case, the more elastic parametrization implies larger effects for all increases of α^g and a more elastic GDP to changes in α^g. In the least elastic case, there are mild average GDP losses that decrease with α^g. Fig. 7(b) shows that the natural gas share increases in all scenarios, and this effect is increasing on both the elasticity and the change in α^g.

7. Policy discussion

Decarbonization and sustainable economic growth are crucial issues in global discussions on climate change. Some studies, such as Narayan et al. (2016), suggest that emissions may decline as economic growth progresses. However, research by González-Álvarez and Montañés (2023) indicates that even if CO_2 emissions are decoupled from economic growth, carbon-intensive energy consumption is on the rise. In this context, natural gas can play a vital role in supporting the transition to renewables, as it is a versatile and flexible energy source that can also serve as a reliable backup during periods of extreme weather variability (see IEA, 2022, Chapter 8). Moreover, the infrastructure used for the transportation and storage of liquefied natural gas can be repurposed for distributing other liquefied gases such as hydrogen (Melaina et al., 2013), further enhancing the sustainability of the energy system.[27]

Therefore, policy reforms such as those we analyze in this paper can have important implications for energy transitions. Our results are also of interest to developing countries, especially Asian countries such as China and India, for which demand for natural gas is expected to increase at least up until 2030. Compared to coal, natural gas emits significantly lower levels of greenhouse gases and other pollutants, making it a cleaner-burning fuel. Given that coal is one of the primary sources of global emissions and widely used in countries such as China and India, substituting it with natural gas in power generation and industrial applications has the potential to reduce emissions and improve

25 Hassler et al. (2012) estimate a measure of energy-saving technical change similar to Γ^g for the U.S. which reacts strongly to oil prices.

26 This is implied by the ratio of Eqs. (7) and (8).

27 Melaina et al. (2013) note that repurposing LNG infrastructure for a blend with hydrogen may require modest modifications to infrastructures. However full conversion to distribute and store hydrogen is substantially more expensive.

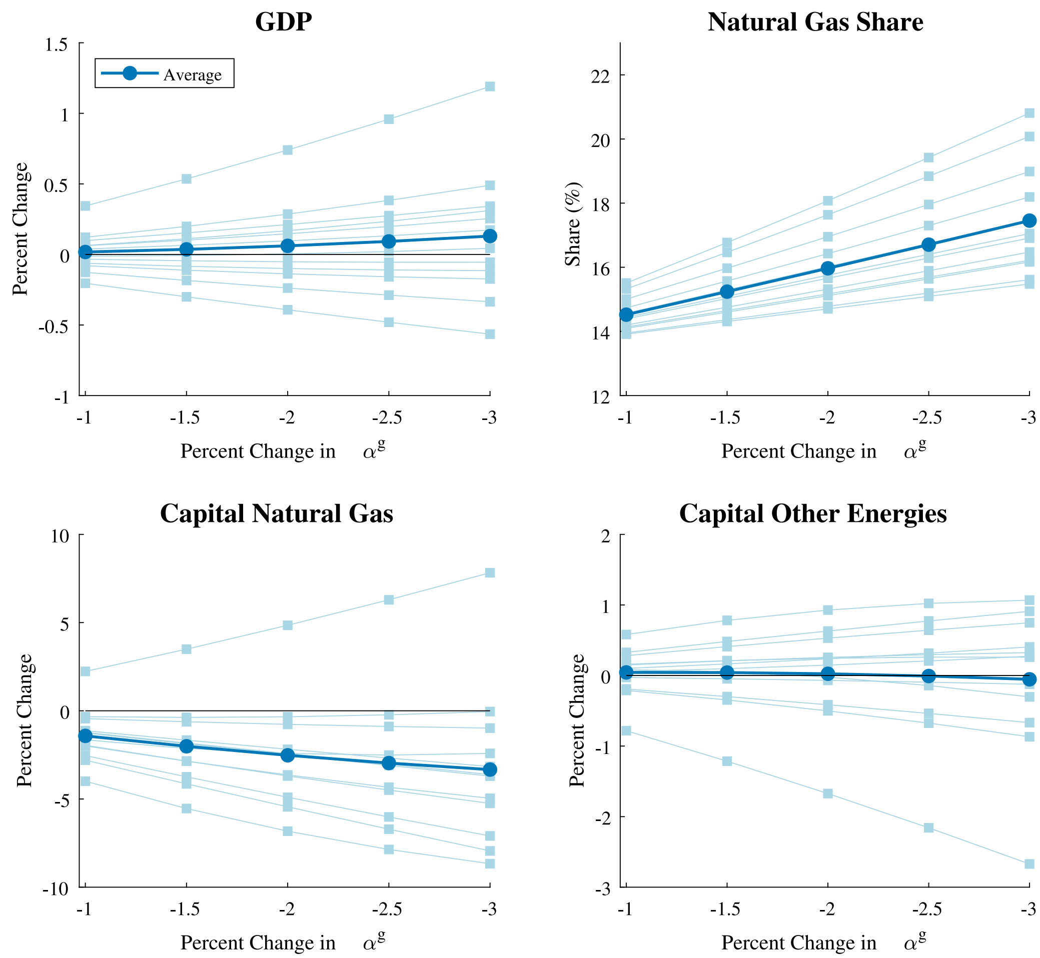
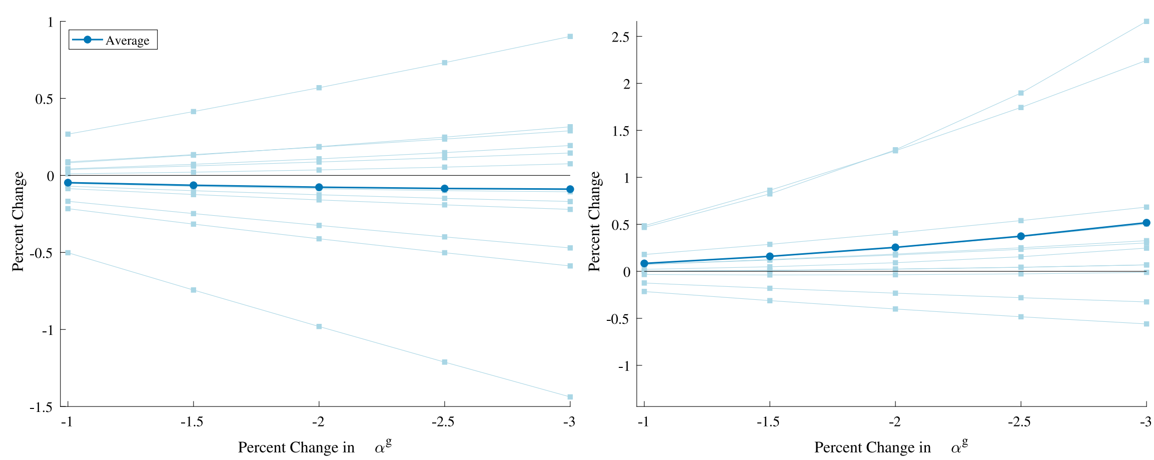


Fig. 5. Effects of an increase in natural gas efficiency.



(a) Elasticity: -1.10 (b) Elasticity: -1.44

Fig. 6. GDP Effects of increasing natural gas efficiency.

air quality. According to our results, reductions in the price of natural gas lead to increased adoption, expansion in capacity investments, and increased natural gas-powered capital. This occurs directly through a reduction in the price that induces a reallocation from other sources toward natural gas. However, these effects fully materialize in the long run since these investments are subject to adjustment costs.

Besides reducing the price of natural gas, increased competition could lead to improvements in natural gas efficiency via innovation. We test this effect within the model and find that this could significantly expand capacity and adoption rates. Moreover, such efficiency improvements lead to GDP gains on average. However, in some cases, natural gas adoption comes at moderate costs to GDP.

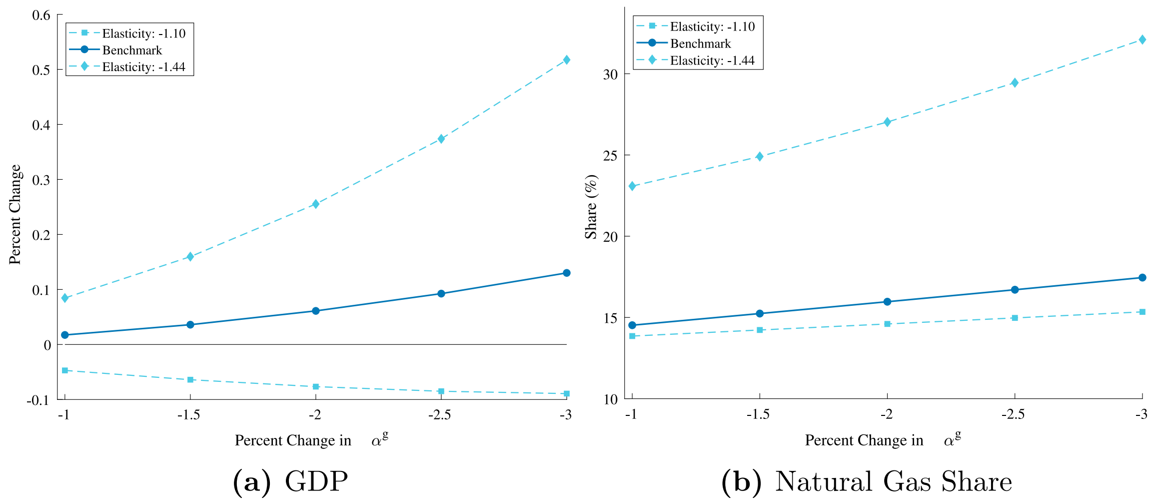


Fig. 7. Increase in natural gas efficiency — Comparison of effects.

In Brazil, natural gas ensures a stable and reliable electricity supply. As a country heavily dependent on hydropower, Brazil's reservoirs are vulnerable to fluctuations in rainfall and water levels, which can lead to an intermittent power supply. One serious example was the 2001–2002 energy crisis, which was a direct result of drought. This crisis resulted in increased tariffs, demand reductions policies (quotas), and significant reductions in revenues of generators and distributors. Natural gas power plants can provide a dependable backup source of electricity when hydroelectric power is limited. Additionally, natural gas can help diversify Brazil's energy mix, reducing dependence on a single source of energy and increasing energy security. Thus, having more natural gas can help mitigate the intermittence of reservoirs and ensure a more consistent electricity supply for Brazil.

Our results suggest that the New Gas Law can lead to a shift toward a more natural gas-intensive economy due to increased competition, potentially aiding the transition to cleaner energy sources such as hydrogen that can benefit from the same infrastructure as natural gas. Overall, regulations that incentivize or mandate the use of natural gas in the short term could help to pave the way for a more sustainable energy system in the long term.

8. Concluding remarks

In this paper, we study the effects of changes to the market structure of natural gas production and its impact at the regional level. We build a dynamic general equilibrium model with heterogeneity in energy inputs and a monopolistic natural gas distribution company. We take the model to the data by calibrating it to 12 of the main Brazilian LDCs and the regional economies they serve. Our model shows how reductions in the price of natural gas can lead to moderate GDP gains in the short and long run. In particular, we find that reducing the price of natural gas by 5% can lead to GDP gains ranging between 0.03% up to 0.16% in the long run. Furthermore, if both the price of natural gas and the price of other energy sources decline by 5%, GDP gains are larger, ranging between 0.38% and 0.44%.

Our results suggest that changes in the demand for natural gas require decades to fully adjust since firms need to substitute capital powered with other sources with capital powered with natural gas. This implies significant and costly investment that takes time to implement. Our model also shows that policies that successfully reduce the price of natural gas can help transition to lower carbon economies. The participation of natural gas in the energy mix can substantially increase if the relative prices change sufficiently. However, our model also shows that a reduction in the price of natural gas is insufficient to generate long-term increases in the participation of natural gas in the energy mix.

Finally, we evaluate another potential effect of increased competition in natural gas: the innovation directed toward natural gas efficiency. We explore this within the model and find that the share of natural gas in the energy mix responds substantially to efficiency improvements. A 1% increase in natural gas efficiency can induce an increase in the share of natural gas of 1.4 percentage points. If efficiency increases by 3%, this number increases to 4.4 percentage points. Thus, innovation increasing the efficiency of natural gas can induce significant adoption.

Our model incorporates heterogeneity across several dimensions and can capture aggregate effects on regional economies. This flexibility can be applied to other settings, such as the natural gas shortages provoked by international conflicts in Europe. A potential extension of our framework beyond the scope of this paper is to assess the size of increased competition necessary to foster sufficient innovation in natural gas. Our results suggest this latter mechanism can be significant for inducing energy transitions in the future.

Declaration of competing interest

We do not have any conflict of interest.

Data availability

Data will be made available on request.

Appendix A. Algorithm for finding the equilibrium

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

$$p^e_t = \pi^e \tag{27}$$

$$\Lambda_t = \frac{1}{1+r_t} \tag{28}$$

$$\varepsilon = \rho \tag{29}$$

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

$$\lambda_t = \Pi^d \left\{ \frac{1}{\Lambda_t}\left[1+\phi^d\left(\frac{G_t}{G_{t-1}}-1\right)\right] - \frac{\phi^d}{2}\left[\left(\frac{G_{t+1}}{G_t}\right)^2-1\right] - \left(1-\delta^d\right)\right\} \tag{30}$$

$$r_t^g = \frac{1}{\Lambda_t}\left[1+\phi^g\left(\frac{k_t^{g,S}}{k_{t-1}^{g,S}}-1\right)\right] - \frac{\phi^g}{2}\left[\left(\frac{k_{t+1}^{g,S}}{k_t^{g,S}}\right)^2-1\right] - (1-\delta^g) \tag{31}$$

$$r_t^e = \frac{1}{\Lambda_t}\left[1+\phi^e\left(\frac{k_t^{e,S}}{k_{t-1}^{e,S}}-1\right)\right] - \frac{\phi^e}{2}\left[\left(\frac{k_{t+1}^{e,S}}{k_t^{e,S}}\right)^2-1\right] - (1-\delta^e) \tag{32}$$

$$p_t^g = \frac{\varepsilon}{\varepsilon-1}\left(\pi_t^g + z^d + \lambda_t\right) \tag{33}$$

$$q_t^g = \frac{1}{A^g}\left[(\alpha^g)^\rho \left(r_t^g\right)^{1-\rho} + (1-\alpha^g)^\rho \left(p_t^g\right)^{1-\rho}\right]^{\frac{1}{1-\rho}} \tag{34}$$

$$q_t^e = \frac{1}{A^e}\left(\frac{r_t^e}{\alpha^e}\right)^{\alpha^e}\left(\frac{p_t^e}{1-\alpha^e}\right)^{1-\alpha^e} \tag{35}$$

$$w_t = (1-\alpha)\left\{A\left[\frac{\alpha}{2\left(q_t^g q_t^e\right)^{\frac{1}{2}}}\right]^\alpha\right\}^{\frac{1}{1-\alpha}} \tag{36}$$

$$q_t = \alpha\left[A\left(\frac{1-\alpha}{w_t}\right)^{1-\alpha}\right]^{\frac{1}{\alpha}} \tag{37}$$

- Update the aggregate energy service:

$$s_t = \left(\frac{w_t}{A(1-\alpha)}\right)^{\frac{1}{\alpha}}\left(\frac{w_t}{\psi}\right)^{\frac{1}{\theta}} \tag{38}$$

- Update the energy service for each energy source:

$$s_t^g = \left(\frac{q_t}{q_t^g}\right)^{\frac{1}{1-\gamma}} s_t \tag{39}$$

$$s_t^e = \left(\frac{q_t}{q_t^e}\right)^{\frac{1}{1-\gamma}} s_t \tag{40}$$

- Update the equipment demand for each energy source:

$$k_t^{g,D} = \frac{1}{A^g}\left(\alpha^g A^g \frac{q_t^g}{r_t^g}\right)^\rho s_t^g \tag{41}$$

$$k_t^{e,D} = \alpha^e \frac{q_t^e}{r_t^e} s_t^e \tag{42}$$

- Update the quantity of natural gas

$$g_t = \left((1-\alpha^g) A^g \frac{q_t^g}{p_t^g}\right)^\rho \frac{s_t^g}{A^g} \tag{43}$$

- 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 toward 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:

$$I_t^d = G_{t+1} - \left(1-\delta^d\right) G_t \tag{44}$$

$$I_t^g = k_{t+1}^{g,S} - \left(1-\delta^d\right) k_t^{g,S} \tag{45}$$

$$I_t^e = k_{t+1}^{e,S} - (1-\delta^e)\, k_t^{e,S} \tag{46}$$

$$e_t = (1-\alpha^e)\frac{q_t^e}{p_t^e} s_t^e \tag{47}$$

$$n_t = \left(\frac{w_t}{\psi}\right)^{\frac{1}{\theta}} \tag{48}$$

$$c_t = w_t n_t \tag{49}$$

$$q_t = \alpha\left[A\left(\frac{1-\alpha}{w_t}\right)^{1-\alpha}\right]^{\frac{1}{\alpha}} \tag{50}$$

$$y_t = \frac{w_t n_t}{1-\alpha} \tag{51}$$

Appendix B. Additional tables

See Table 17.

Table 17
Calibration targets.

LDC	Targets for each moment						
	Price Elasticity	NG share	GDP	Capital income	NG rel. eff.	Labor	Relative Capital Services
Sulgás	−1.250	0.131	1.000	0.896	1.266	0.262	0.191
SCGás	−1.250	0.131	1.000	0.896	1.266	0.262	0.191
Compagás	−1.250	0.131	1.000	0.896	1.266	0.262	0.191
Comgás	−1.250	0.131	1.000	0.896	1.266	0.262	0.191
Gás Brasiliano	−1.250	0.131	1.000	0.896	1.266	0.262	0.191
Naturgy São Paulo	−1.250	0.131	1.000	0.896	1.266	0.262	0.191
Naturgy Rio Capital	−1.250	0.131	1.000	0.896	1.266	0.262	0.191
Naturgy Rio Interior	−1.250	0.131	1.000	0.896	1.266	0.262	0.191
Gasmig	−1.250	0.131	1.000	0.896	1.266	0.262	0.191
MSGás	−1.250	0.131	1.000	0.896	1.266	0.262	0.191
Bahiagás	−1.250	0.131	1.000	0.896	1.266	0.262	0.191
Copergás	−1.250	0.131	1.000	0.896	1.266	0.262	0.191

Appendix C. Transitions for each LDC

C.1. Sulgás

See Fig. 8.

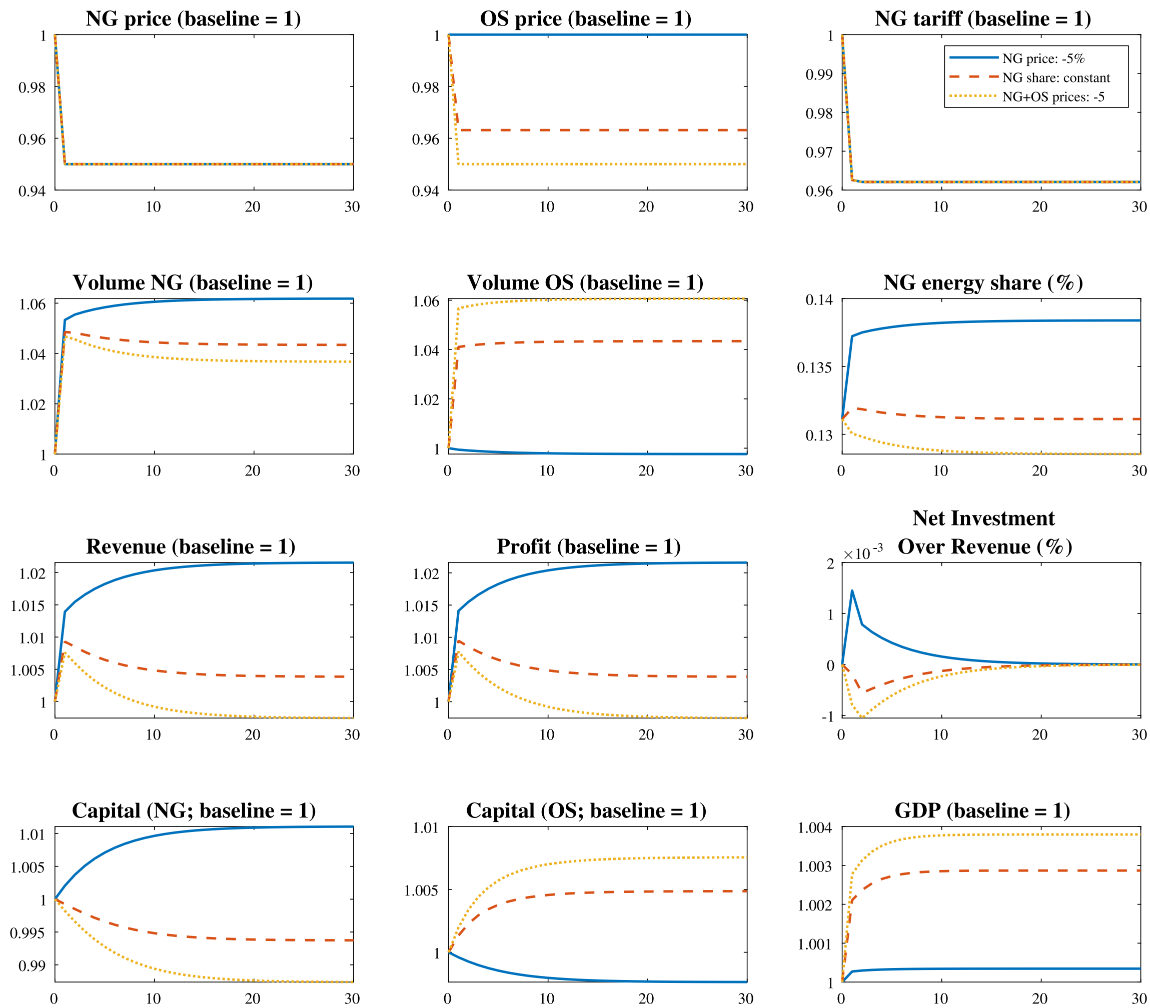


Fig. 8. Transitions for Sulgás.

C.2. SCGás

See Fig. 9.

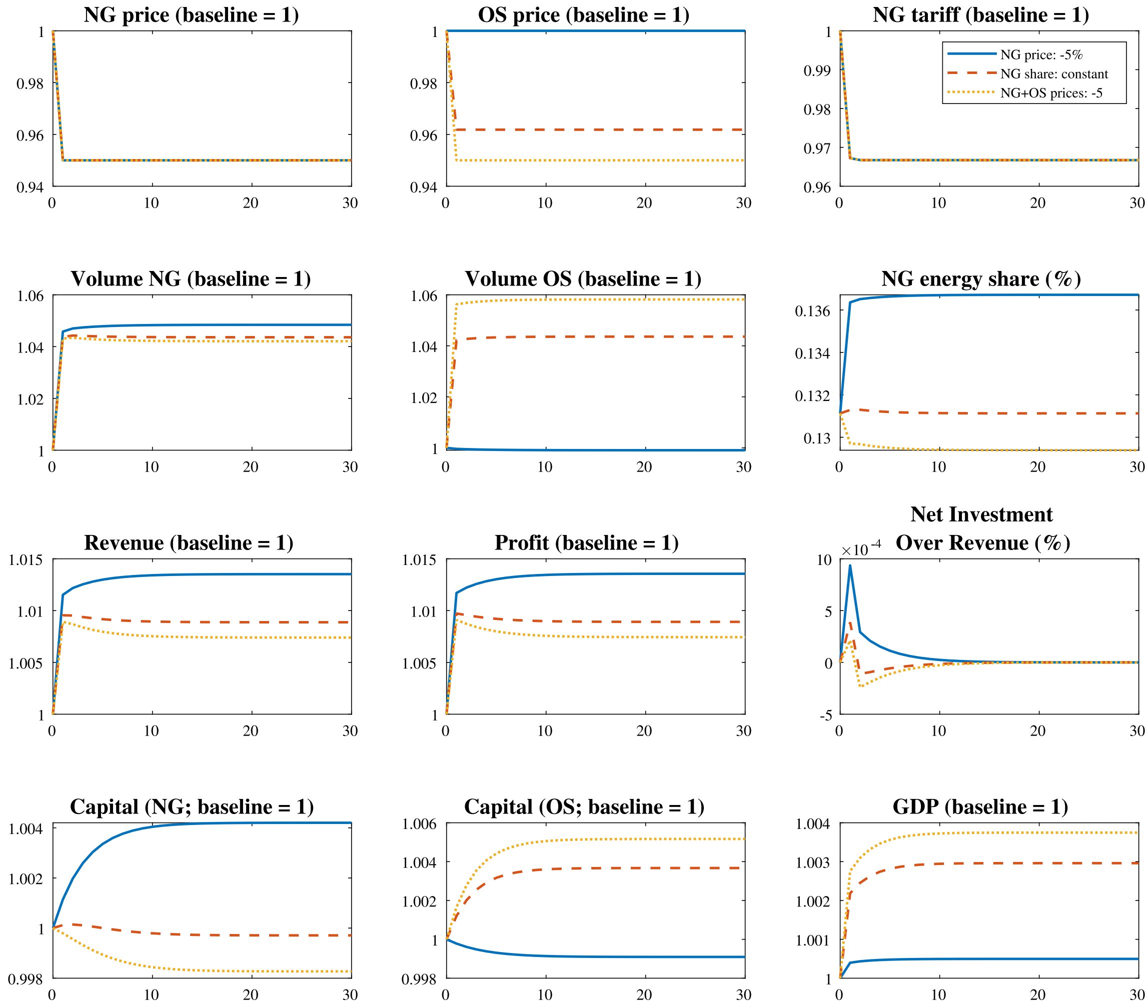


Fig. 9. Transitions for SCGás.

C.3. Compagás

See Fig. 10.

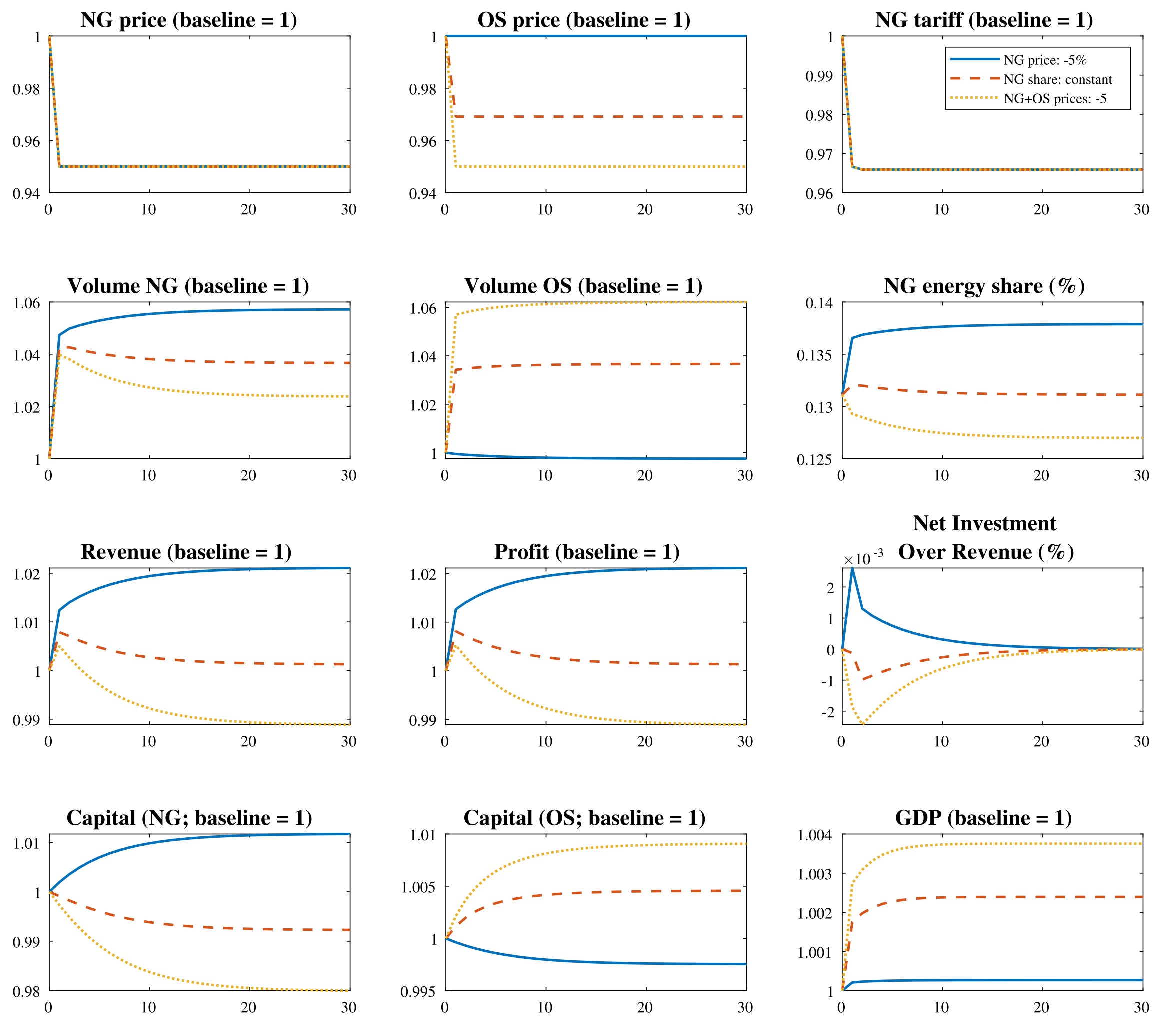


Fig. 10. Transitions for Compagás.

C.4. Comgás

See Fig. 11.

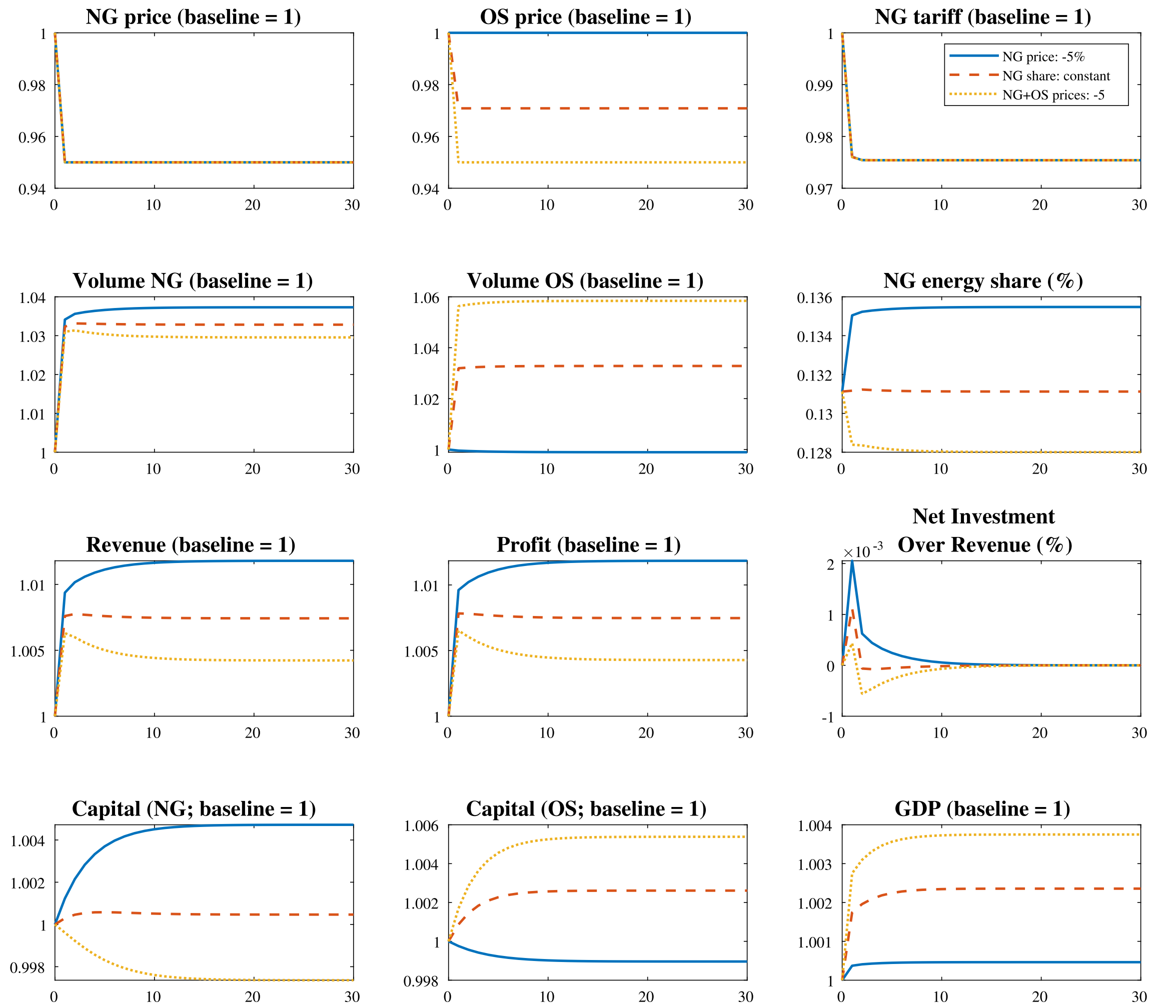


Fig. 11. Transitions for Comgás.

C.5. *Gás Brasiliano*

See Fig. 12.

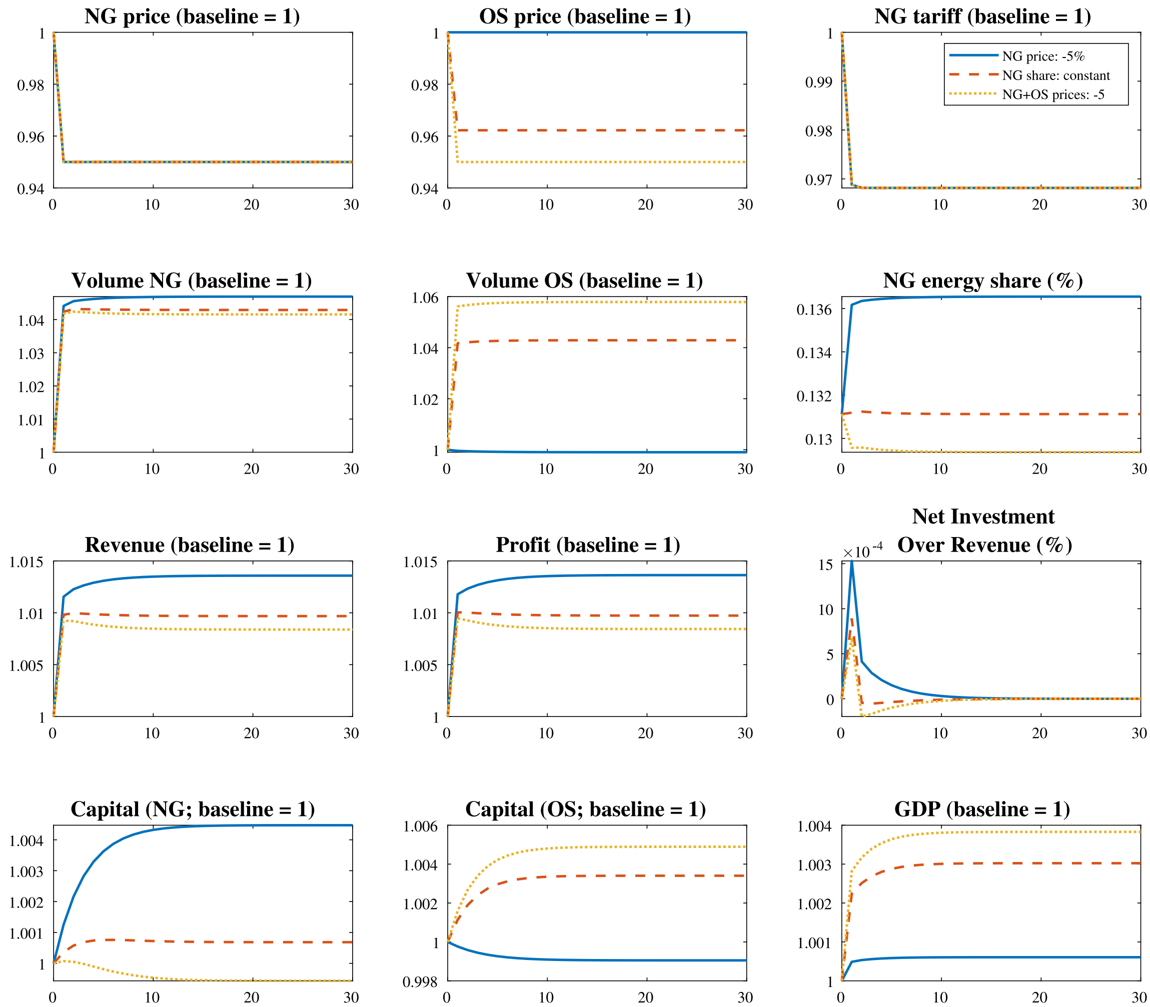


Fig. 12. Transitions for Gás Brasiliano.

C.6. Naturgy São Paulo

See Fig. 13.

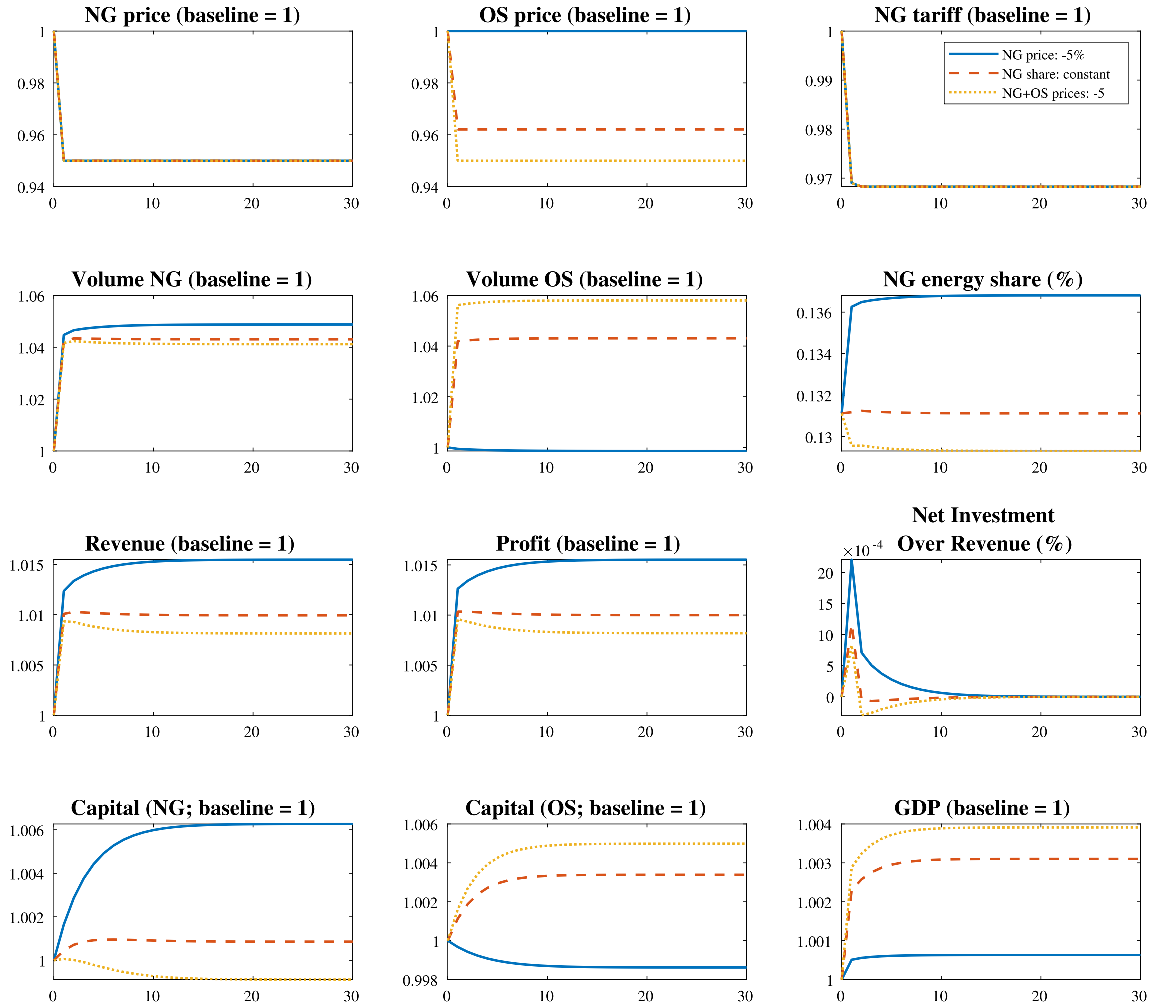


Fig. 13. Transitions for Naturgy São Paulo.

C.7. Naturgy Rio Capital

See Fig. 14.

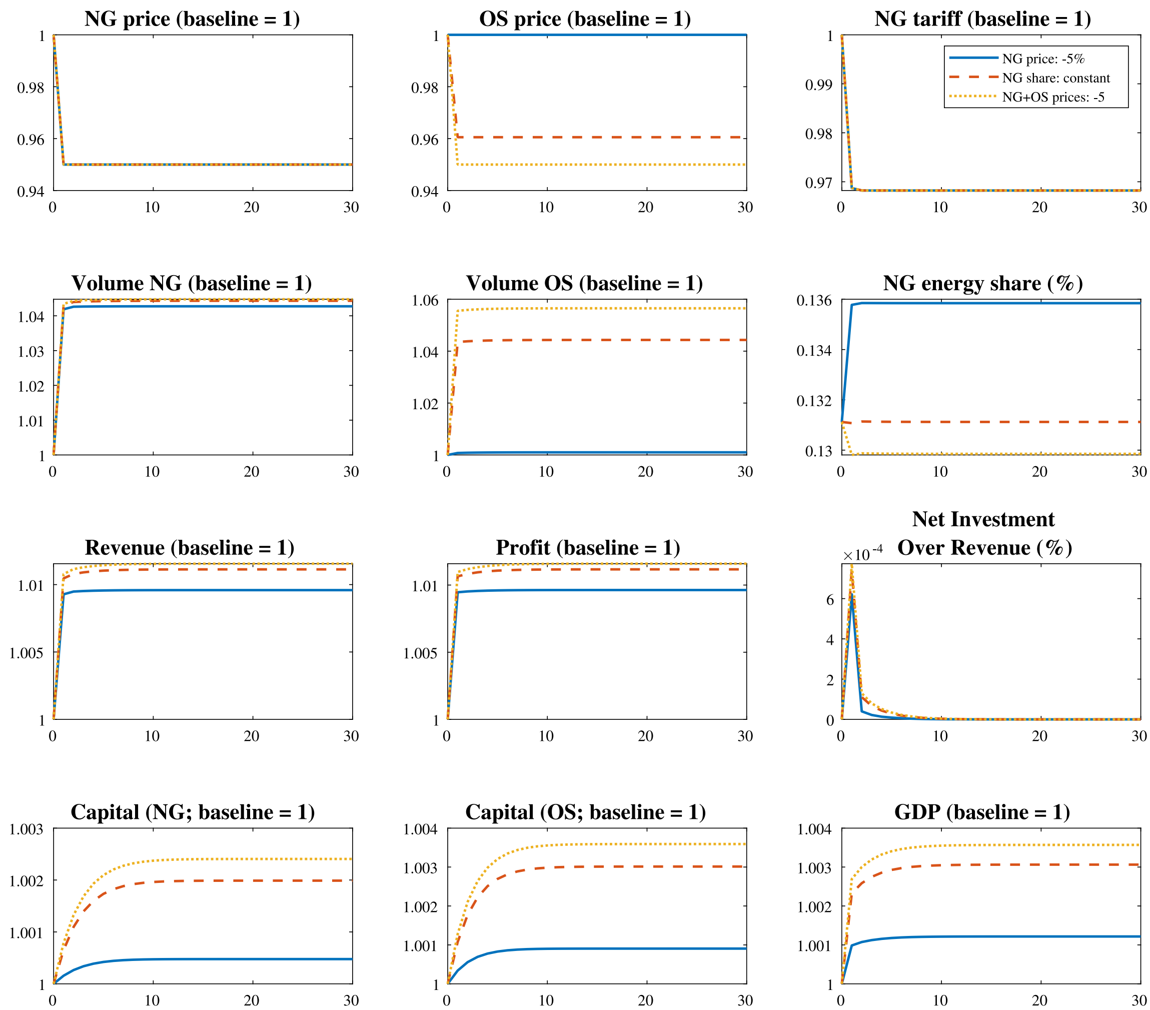


Fig. 14. Transitions for Naturgy Rio Capital.

C.8. Naturgy Rio Interior

See Fig. 15.

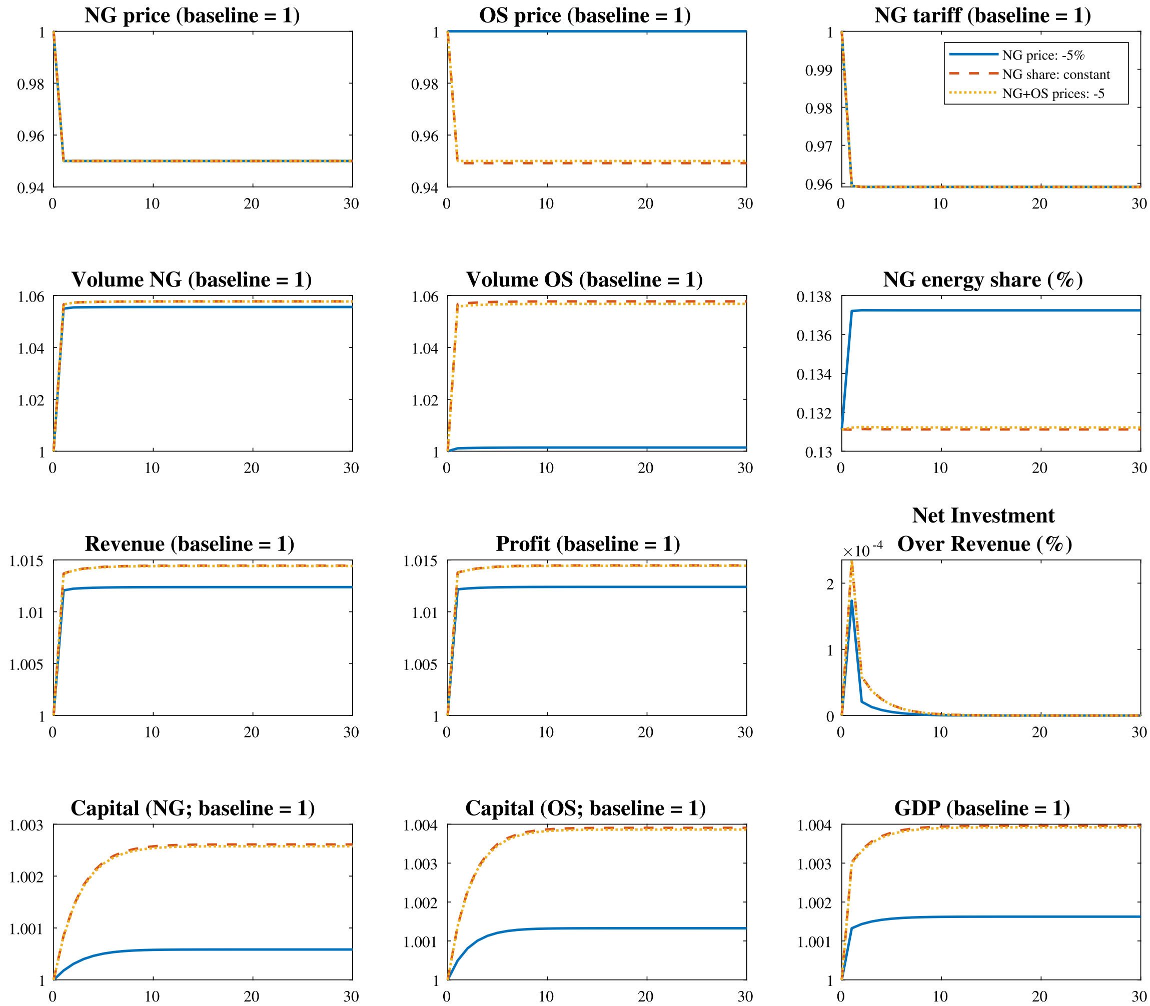


Fig. 15. Transitions for Naturgy Rio Interior.

C.9. Gasmig

See Fig. 16.

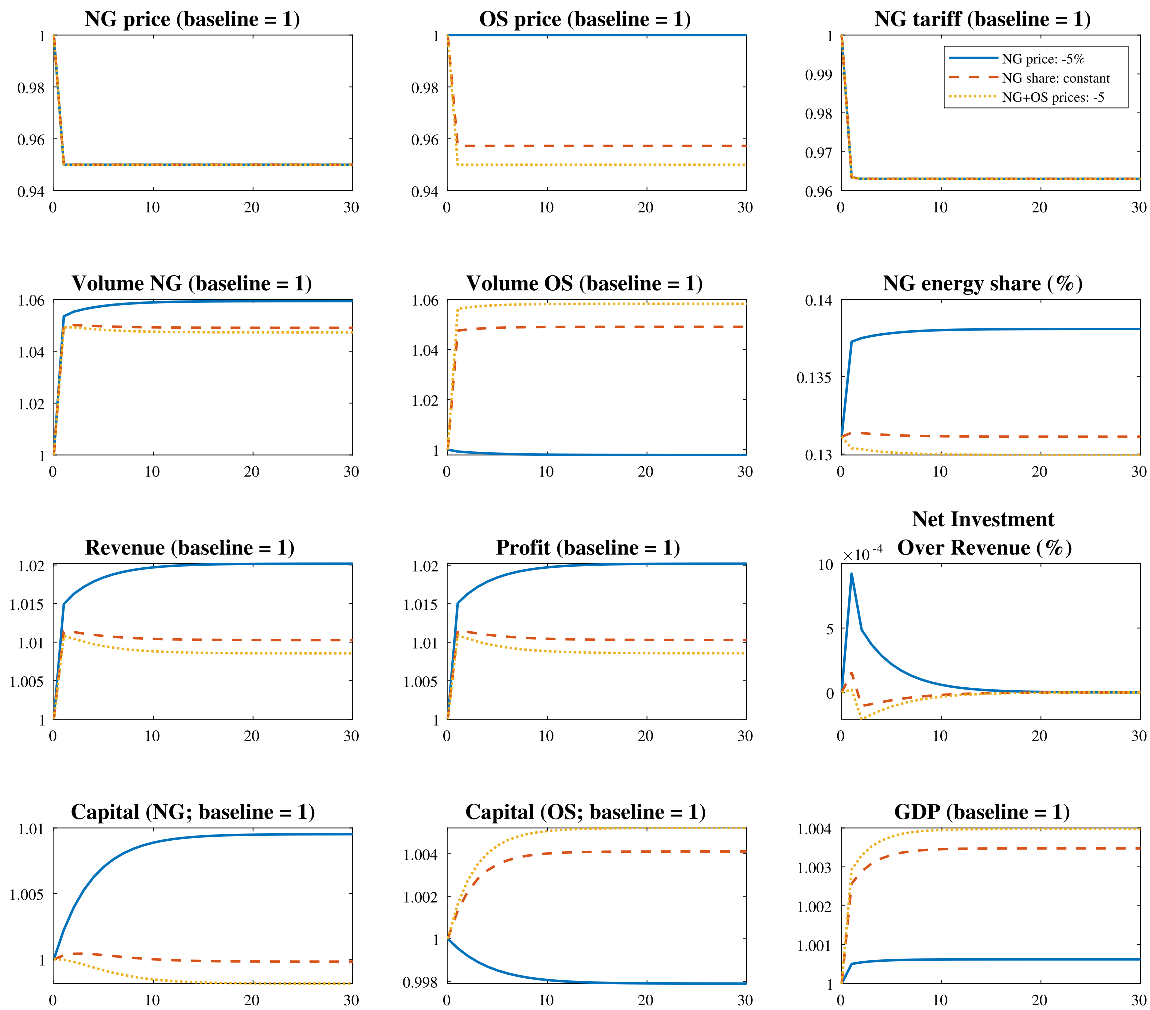


Fig. 16. Transitions for Gasmig.

C.10. MSGás

See Fig. 17.

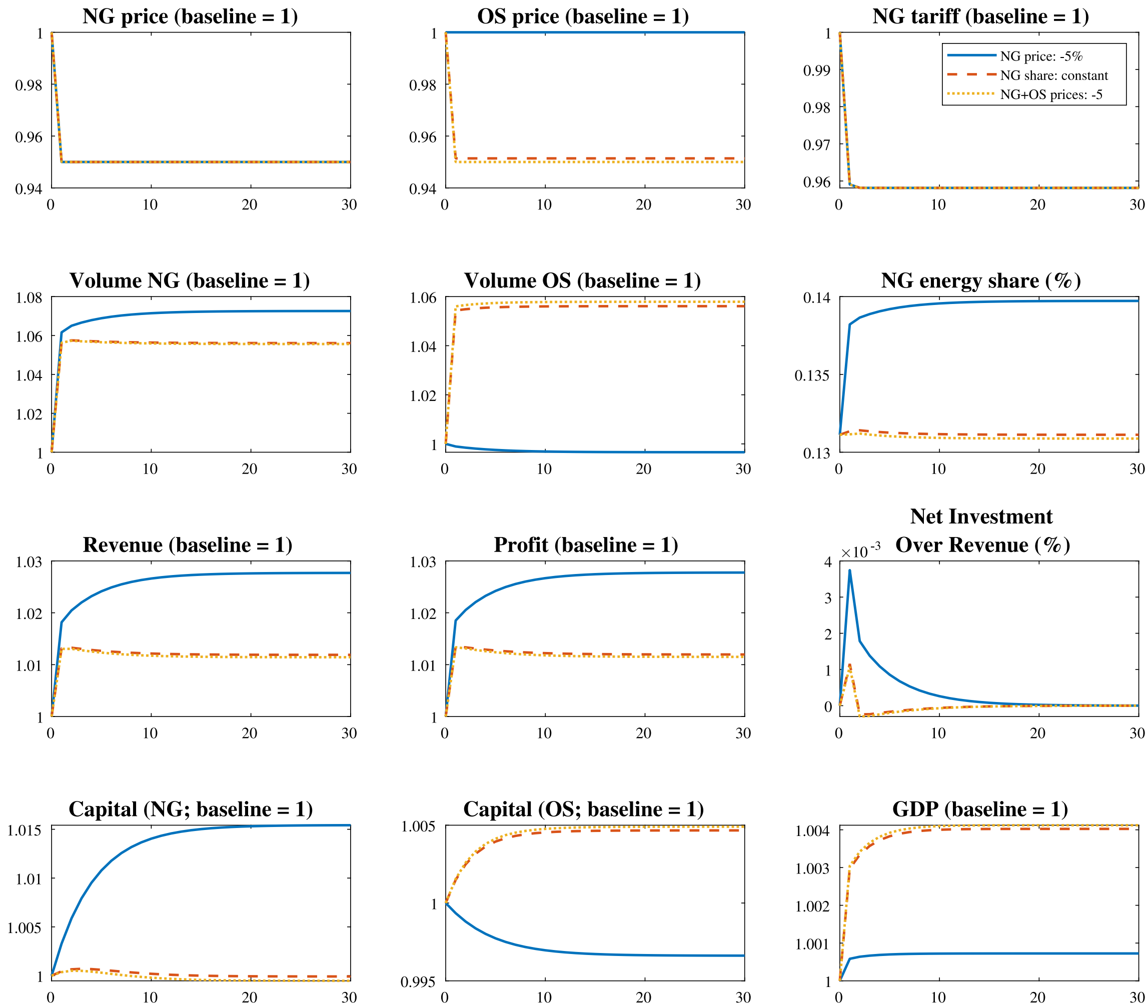


Fig. 17. Transitions for MSGás.

C.11. Bahiagás

See Fig. 18.

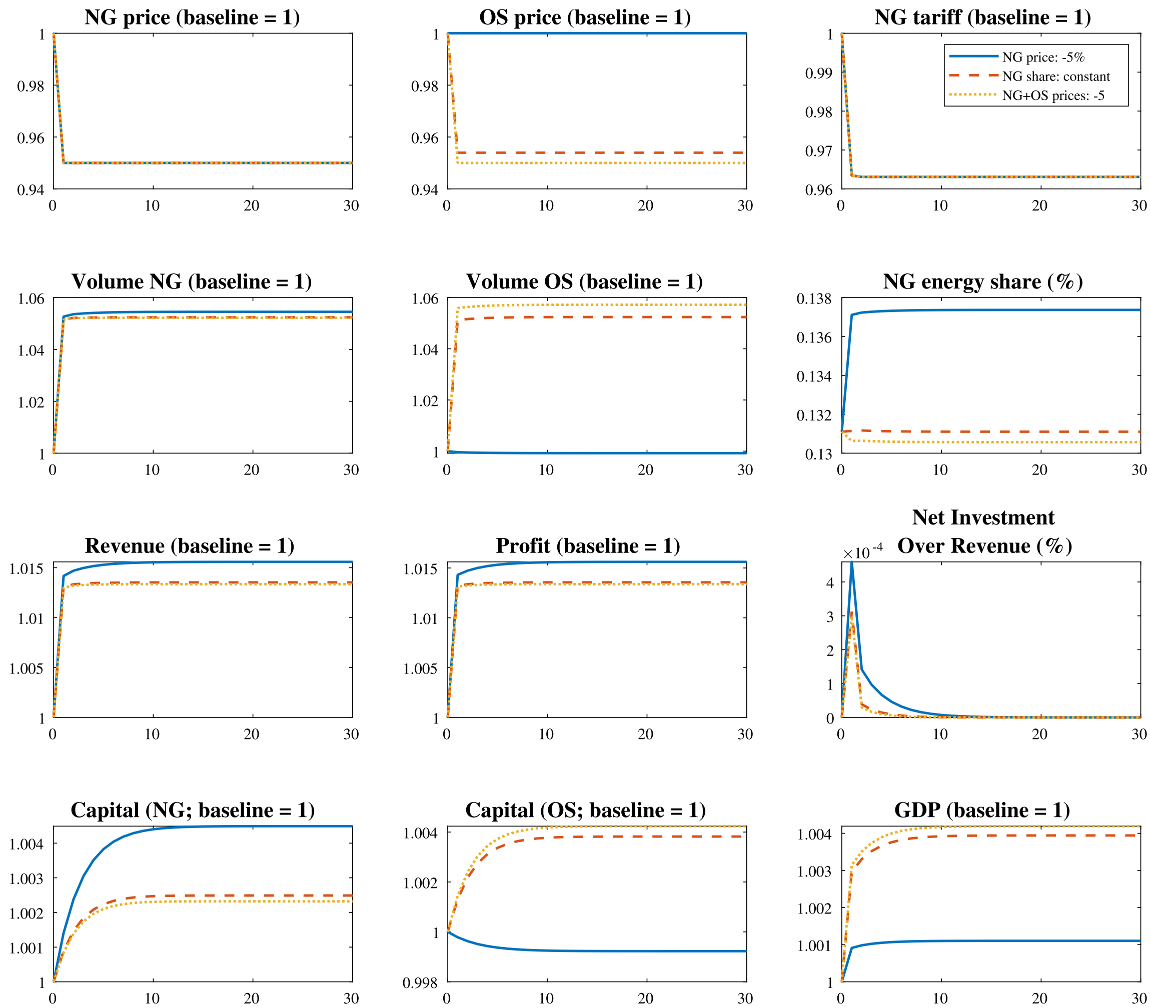


Fig. 18. Transitions for Bahiagás.

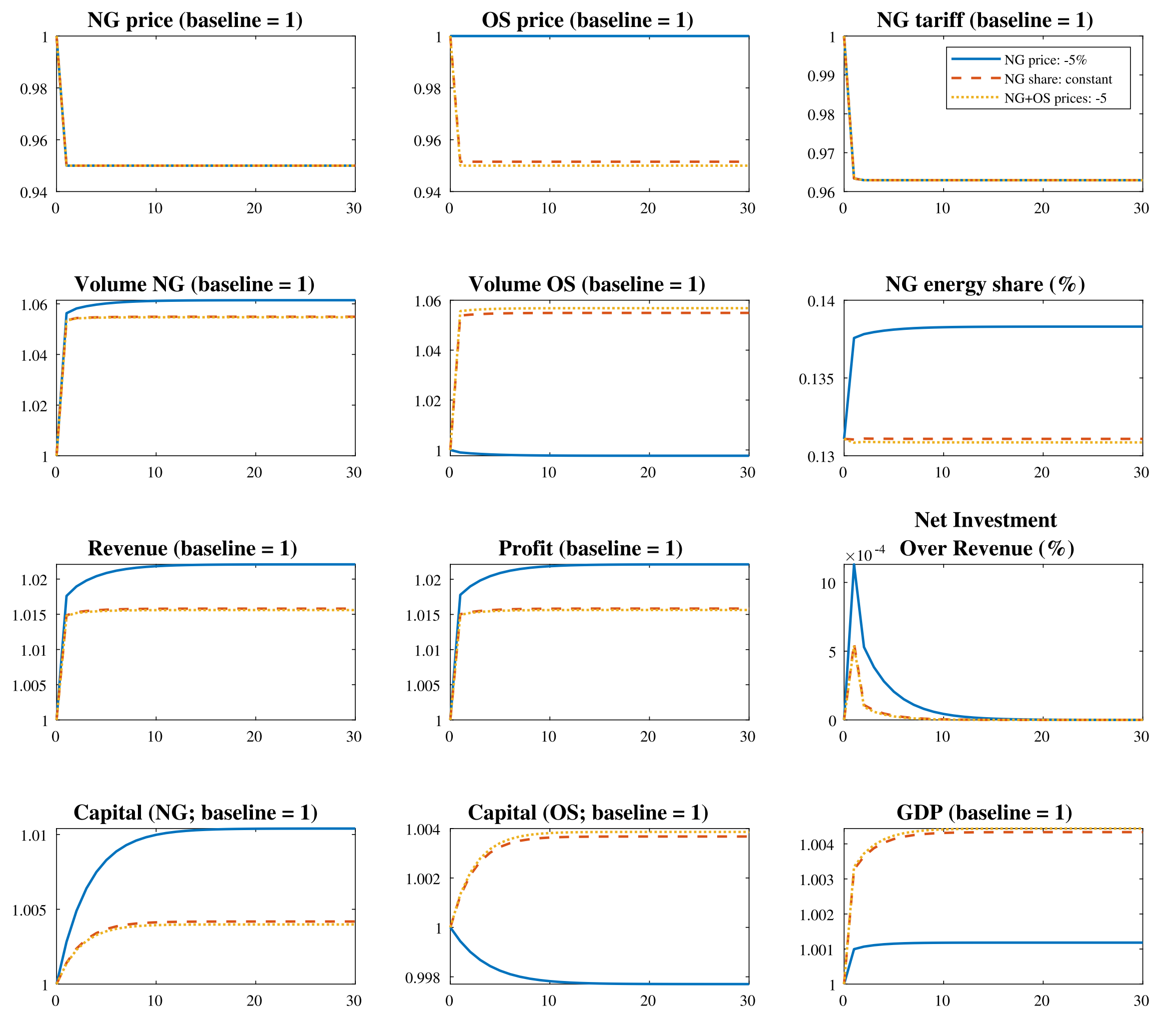


Fig. 19. Transitions for Copergás.

C.12. Copergás

See Fig. 19.

Appendix D. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.econmod.2023.106358.

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