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MIRAGE Model Documentation Version 2.0

Antoine Bouët, Lionel Fontagné, Christophe Gouel, Houssein Guimbard,
Cristina Mitaritonna, Balthazar de Vaulchier & Yu Zheng

Highlights

- MIRAGE is a multi-sector, multi-region computable general equilibrium model designed for economic policy analysis, particularly focusing on trade and environmental policies.
- The model features advanced trade modeling capabilities with detailed treatment of trade costs, Armington specifications, and analysis of trade barriers through the MAcMap-HS6 database.
- Enhanced energy sector representation includes detailed electricity generation modeling with renewable energy integration considering base-load and peak-load, capital-energy bundles, and greenhouse gas emissions accounting with carbon market mechanisms.
- The sequential dynamic framework enables long-term economic projections by combining total factor productivity calibration with macroeconomic forecasts from the MaGE model for consistent policy scenario analysis.

RESEARCH AND EXPERTISE
ON THE WORLD ECONOMY

Abstract

MIRAGE is a multi-region, multi-sector computable general equilibrium (CGE) model, initially devoted to trade policy analysis and more recently applied to long-term growth and environmental issues. It incorporates energy, carbon pricing, imperfect competition, and rigid investment allocation, in a sequential dynamic setup where installed capital is assumed to be immobile. The model provides trade analysis with detailed treatment of trade costs and Armington specifications, drawing upon a detailed measure of trade barriers through the MAcMap-HS6 database. Production features nested CES functions with capital-energy bundles under both perfect and imperfect competition frameworks, while final demand follows a LES-CES utility function. The sequential dynamic framework enables long-term simulations by combining total factor productivity calibration with macroeconomic projections from the MaGE model. The most recent version offers significant improvements in electricity sector modeling with renewable energy representation, base-load and peak-load dinstinctions, and detailed greenhouse gas (GHG) emissions accounting with carbon market mechanisms. This documentation provides complete technical specifications, calibration procedures, and implementation guidelines for researchers and policymakers using MIRAGE for economic policy analysis.

Keywords

Computable General Equilibrium, Trade Policy, Environnemental Policy.

JEL

C68, F1, Q54, Q56, Q40, Q42.

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Centre d'études prospectives
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20, avenue de Ségur
TSA 10726
75334 Paris Cedex 07

contact@cepii.fr
www.cepii.fr – @CEPII_Paris
Press contact: presse@cepii.fr

MIRAGE model documentation
Version 2.0*

Antoine Bouët[1], Lionel Fontagné[2], Christophe Gouel[3,1], Houssein Guimbard[1], Cristina Mitaritonna[1], Balthazar de Vaulchier[1], and Yu Zheng[1]

[1]CEPII, 20 avenue de Ségur, 75007, Paris, France
[2]Paris School of Economics, 48 boulevard Jourdan, 75014, Paris, France
[3]Université Paris-Saclay, INRAE, AgroParisTech, Paris-Saclay Applied Economics, 91120, Palaiseau, France

*The list of authors corresponds to the MIRAGE team in its current configuration and to recent contributors. However, the model is a collective work that would not exist without the previous contributors. We are grateful to the previous team members for their contributions: Mohamed Hedi Bchir, Cecilia Bellora, Yvan Decreux, Jean Fouré, Jean-Louis Guérin, Sébastien Jean, David Laborde, Maria Priscila Ramos, Julie Schlick, and Hugo Valin.

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Model history

The primary motivation that led Cepii to develop the Mirage (Modelling International Relationships in Applied General Equilibrium) model in 2001 was the need for an appropriate model to analyze the consequences of trade policy reforms.

Compared with the two similar multi-sectoral and multi-regional computable general equilibrium (cge) models in existence at the time—Linkage at the World Bank and gtap at Purdue—Mirage introduced several innovations. On the modeling side, Mirage incorporates imperfect competition, product differentiation by variety and quality, and foreign direct investment in a sequential dynamic set-up (Bchir et al. 2002). On the data side (calibration and counterfactual scenarios), Mirage draws on a very detailed measure of tariff barriers, enabled by the in-house development of the MAcMap-HS6 (Market Access Map HS6) database (Bouët, Decreux, et al. 2008; Guimbard et al. 2012).

Since trade policy negotiations focus heavily on agricultural issues, it was necessary to represent this sector in greater detail. That is why, in 2007, Mirage was expanded to better assess trade policy effects in agricultural sectors by introducing new modeling of export subsidies, intervention prices, and production quotas in the European Union; imperfect land allocation across different crops; capital and land subsidies; and imperfect labor mobility between agricultural and non-agricultural sectors. At the same time, the model's dynamic framework was improved. The labor reservoir was adjusted according to United Nations forecasts, and total factor productivity growth was calibrated to match World Bank economic growth forecasts. For developing countries, migration from rural to urban areas was also accounted for (Decreux and Valin 2007).

Given the complexity of the negotiations on the Doha Round agenda and the proliferation of deep regional agreements worldwide, Mirage also began to include various measures of trade barriers beyond tariffs. These include estimates of protection in services (Fontagné, Mitaritonna, et al. 2016), ad valorem equivalents of non-tariff measures in goods, and estimates of the administrative and transaction costs that would be reduced by trade facilitation measures (Bouët and Laborde 2010; Decreux and Fontagné 2015).

Since 2012, Mirage has moved forward to address long-term issues: energy efficiency and prices, agricultural productivity, and CO_2 emissions. These features were incorporated in a new version of the model, Mirage-e. For Mirage-e and subsequent versions, the dynamic baseline follows the macroeconomic projections of the MaGE model (Fontagné, Fouré, et al. 2013; Fontagné, Perego, et al. 2022; Fouré et al. 2013).

The interactions between trade and environmental policies have recently become an important subject for Cepii's research agenda, spurring a new wave of developments, in particular two distinct versions of the model: Mirage-VA and Mirage-Power, both embedding a detailed representation of greenhouse gas emissions. Mirage-VA explicitly models global value chains, while Mirage-Power includes renewable and nuclear energy as possible sources for electricity generation. Both models can activate specific climate policy features such as the EU Emission Trading System and the Carbon Border Adjustment Mechanism (Bellora and Fontagné 2023).

The version of Mirage documented here is based on Mirage-Power. To avoid the proliferation of variants and associated names, we are returning the model to its original name, and future Mirage versions will be modular so as to integrate the different variants into a single framework.

1 Introduction

Mirage is a multi-region, multi-sector computable general equilibrium (cge) model, initially devoted to trade policy analysis and more recently applied to long-term growth and environmental issues. It incorporates energy, carbon tax, imperfect competition, and rigid investment allocation, in a sequential dynamic setup where installed capital is assumed to be immobile. Mirage draws upon a very detailed measure of trade barriers and their evolution under given hypotheses, thanks to the MAcMap-HS6 database. The most recent version, presented in this document, offers improvements in the modeling of the electricity generating sector and greenhouse gas (ghg) emissions.

For calibration, Mirage relies on the gtap database. In a nutshell, the model exhibits the following structure:

- Final demand is modeled by a representative agent, which includes both consumers and the government, and which maximizes an les-ces utility function.
- The supply side is represented by firms (under perfect or imperfect competition). Firms in each sector maximize their profit function with their production function composed of nested ces functions.
- Energy is paired with capital in a capital-energy (KE) bundle. Electricity supply is aggregated to meet electricity demand from firms and consumers. Electricity generation benefits from a rich structure, with a nesting split between base and peak load production. This framework is particularly suited to account for the specific features of intermittent renewables or the bottleneck characteristics of some peak load energies.
- Trade is implemented with a two-level Armington-type specification, introducing a home bias compared to other countries. Mirage being initially devoted to trade policy analysis, great care is given to trade barriers, be they tariff or non-tariff measures. Specific data sets are used in that case, instead of the gtap database. International transportation of goods is also modeled.
- Dynamics is based on a sequential nature: the equilibrium can be solved successively for each period. The time span can be freely chosen, usually around 15 to 20 years. Depending on the factors, their growth rate is set either exogenously or endogenously, and the technical progress is calibrated in order to fit gross domestic product (gdp) forecast from the EconMap database—which is itself a product of the MaGE model. At each period, labor, land and the number of varieties adjust instantaneously to match the objectives assumed in the model. By contrast, capital stocks only adjust through investment, so that rates of return vary across sectors after the base year.
- ghg emissions are computed using sector-specific emission factors or are associated with the production process. Carbon markets can be introduced in the model, with

carbon emission targets or explicit carbon pricing. This feature allows MIRAGE to simulate environmental policies.

The rest of this documentation describes the detailed structure of the model in Section 2, then presents the data needed at calibration time in Section 3, before delving into the baseline steps in Section 4. Finally, all the parameters, variables, and equations of the model can be found in the Appendix.

2 Model structure

MIRAGE is a multiregional and multisectoral model, the regional and sectoral aggregation of which can be adapted to each application. This section describes the structure of the model and focuses on a few key assumptions, namely those dealing with trade, transport, imperfect competition, investment allocation, and dynamic aspects. The model's equations are displayed throughout this section when needed for a better understanding; all the equations are also summarized in Section B. In the following, superscripts for prices P and share parameters s refer to the related quantity. The same convention applies for elasticities σ, where the superscript indicates the output variable of the CES nest. Finally, the notations for indices are as follows: i, j denote sectors, r, s are regions, and t is time.

2.1 Final demand

In each region, a representative agent allocates a fixed share of the regional income to savings and purchases goods for final consumption with the rest of the income. The saving rates follow projections by MaGE.[1] The utility function of this agent is intratemporal.

The representative agent encompasses both the government and final consumers. Therefore, the representative agent both pays and collects taxes. Furthermore, no public budget constraint is explicitly considered; instead, this constraint is implicitly addressed to satisfy the representative agent's budget constraint. Consequently, unless otherwise specified, any decrease in tax revenues (for example, as a result of trade liberalization) is offset by a non-distortive replacement tax. However, the magnitude of the losses in tax revenues in case of phasing-out tariffs is an important piece of information, provided in standard result tables.

We consider that final per capita consumption follows a nesting of CES and LES demand functions (see Fig. 1 for a graphical representation). This extension of LES to the slightly more flexible framework of the CES was first proposed by Pollak (1971). Without excessive complexity, this allows us to account for the evolution of the demand structure of each region as its income level changes. With this kind of utility function, the elasticity

[1] See Section 4 for details about MaGE and the EconMap database.

of substitution is constant only for the discretionary consumption levels, the sectoral consumptions over and above a minimum level. This LES-CES can be expressed by the following program:

$$\max_{C_{irt}} U_{rt} = \left[\sum_i \alpha^C_{ir} \left(\frac{C_{irt}}{Pop_{rt}} - \bar{c_{ir}} \right)^{(\sigma^C_r - 1)/\sigma^C_r} \right]^{\sigma^C_r/(\sigma^C_r - 1)} , \tag{1}$$

subject to $\sum_i P^C_{irt} C_{irt} = BudC_{rt}$. The consumer demands for each sector i an incompressible level $\bar{c}_{ir}$. She allocates the remaining part of her income $BudC_{rt}$ according to the CES demand function with elasticity σ^C_r. C_{irt} represents the consumption of sector i, including incompressible consumption. P^C_{irt} is the price of consumption, while P^U_{irt} is the shadow price of utility. Finally, total population Pop_{rt} divides consumption to obtain the consumption per capita variable.

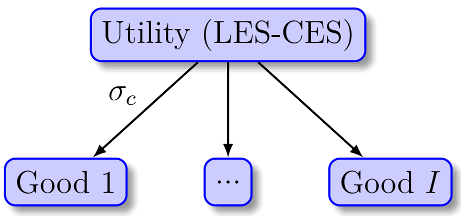


Figure 1: Utility function

The LES-CES function inherits from the LES function the possibility to be calibrated on any positive income elasticity (see Section 3.4 for details on the calibration procedure). With income growth, the LES-CES converges to a CES. Own-price elasticities are strongly linked to income elasticities: sectors with low income elasticity have a high incompressible consumption. Since most of their consumption is fixed, except for a very high elasticity of substitution in the CES nest, these sectors have a low own-price elasticity. Finally, regularity requires that income be superior to the cost of subsistence $\sum_i P^C_{irt} \bar{c}_{ir}$.

2.2 Supply and intermediate demand

In this section, the structure of the various production functions is described, along with the different factors involved in production.

2.2.1 Production factors

Production makes use of five factors: capital, skilled labor, unskilled labor, land and natural resources. Factor endowments are assumed to be fully employed. These factors grow year after year, with the following growth rates:

- Natural resources:

  - Constant for sectors other than primary fossil production
  - Calibrated in the baseline for primary fossil energy (coal, oil, gas)
- Labor: Exogenous growth based on EconMap, differentiated by skill level
- Land: Endogenous to the model, based on an isoelastic function of the real return to land (Lee and Mensbrugghe 2001)
- Capital: Endogenous to the model (see Section 2.7), determined by domestic savings (exogenous share of revenue) and current account (exogenous share of world GDP), both projected by EconMap.

Land supply

In the standard version of the model, land is considered as imperfectly mobile. Land substitution is governed by a Constant Elasticity of Transformation (CET) function assigning land to the best remunerating agricultural productions with an elasticity of 0.5:

$$\begin{cases} \max W_{rt}^{Land\text{TOT}} Land_{rt}^{\text{TOT}} = \sum_i W_{irt}^{Land} Land_{irt} , \\ \text{s.t.} \quad (Land_{rt}^{\text{TOT}})^{1+1/\sigma^{Land}} = \sum_i b_{ir}^{TE} Land_{irt}^{1+1/\sigma^{Land}} , \end{cases} \tag{2}$$

where total land supply is

$$Land_{rt}^{\text{TOT}} = LandO_{rt}^{\text{TOT}} \left(\frac{W_{rt}^{Land\text{TOT}}}{P_{rt}^{U}} \right)^{\sigma_r^{Land\text{TOT}}} . \tag{3}$$

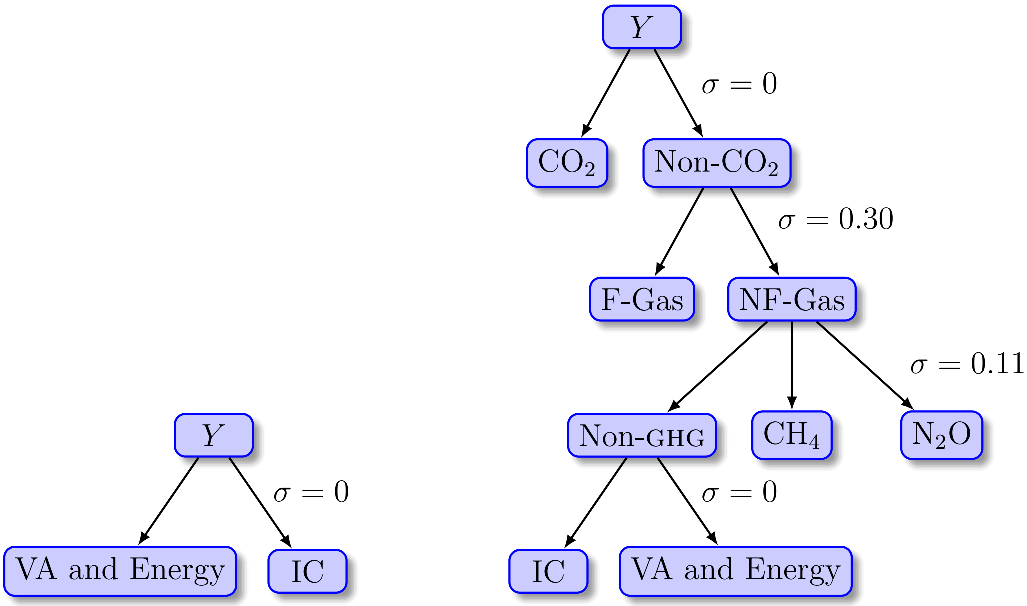
W_{rt} is the standard notation for factor rates of return.

Labor supply

The MIRAGE model considers that unskilled labor is not perfectly mobile between rural and urban sectors. This specificity was developed to better describe likely frictions during trade liberalization. As a result, the demand for different types of labor follows a CET function:

$$\begin{cases} \min W_{rt}^{UnskL\text{TOT}} UnskL^{\text{TOT}}{}_{rt} = \sum_{Ltype} W_{Ltype,rt}^{Lt} Lt_{Ltype,rt} , \\ \text{s.t.} \quad UnskL^{\text{TOT}}{}_{rt}^{1+\frac{1}{\sigma^L}} = \sum_{Ltype} b_{Ltype,r}^{Lt} Lt_{Ltype,rt}^{1+\frac{1}{\sigma^L}} , \end{cases} \tag{4}$$

where $Lt_{Ltype,rt}$ is the labor supply of a given type, and $Ltype$ runs over two types of labor, urban and rural (whose sectors are determined in the aggregation process).



(a) Legacy (b) Standard

Figure 2: Top-level nesting for legacy and standard MIRAGE production function
In this figure, Y is the production of a given sector, VA stands for value added, IC for intermediate consumption, GHG for greenhouse gas, and F-Gas for fluorinated gas.

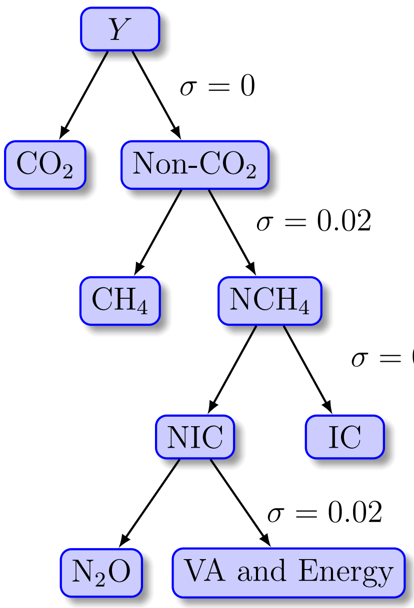
2.2.2 Substitutions in the production chains

Unlike previous versions of the MIRAGE model, different sectors now have very different production functions, mainly due to their different behavior towards non-CO_2 emissions. To classify the different sectors and model their production function, MIRAGE mainly follows Hyman et al. (2003). This results in six different production functions that only differ by their top-level nesting (see Figs. 2 and 3):

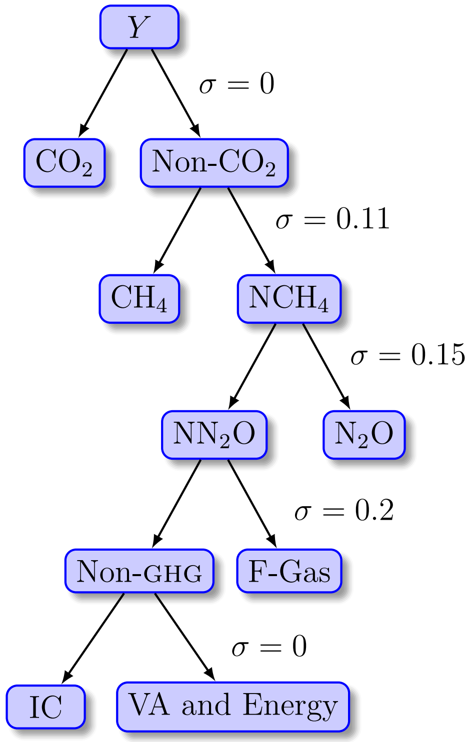
- Legacy MIRAGE top-tier (used only when aggregation does not follow the requirements for non-CO_2 GHG),
- Non-energy, non-agriculture production (aka "standard"),
- Energy-intensive manufacturing,
- Agriculture and forest,
- Fossil production,
- Fossil electricity generation.

Top-level of production function

The top level of the production function varies from one sector to another. The different alternatives are shown in Figs. 2 to 4. In these figures, each box corresponds to a

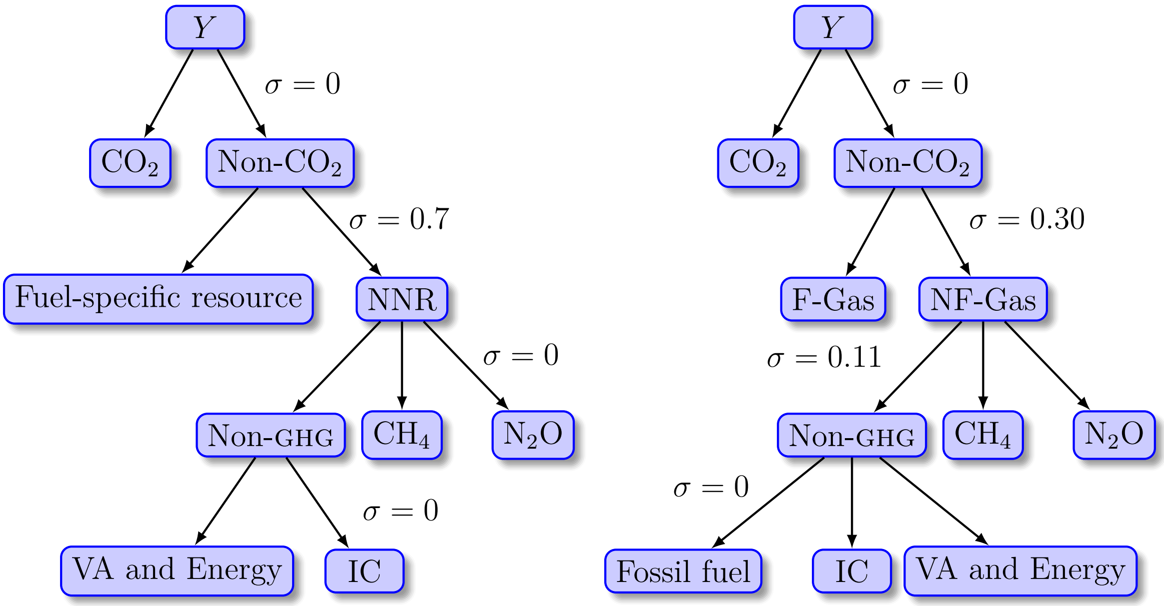


(a) Agriculture & forest



(b) Energy-intensive

Figure 3: Top-level nesting for Agriculture and forest, and energy-intensive sectors of Mirage production function



(a) Fossil production (b) Fossil electricity

Figure 4: Top-level nesting for fossil production and electricity MIRAGE production function

MIRAGE variable, and arrows denote the aggregation relation, most often a CES aggregate. Elasticities of substitution are shown with the different values for σ ($\sigma = 0$ means the functional form is Leontief). These values are also regrouped in Section 3.3.

- Y is the total production of a given sector.
- VA corresponds to the value-added and energy bundle (see Fig. 5).
- IC corresponds to the intermediate consumption bundle (see Fig. 6).
- Other bundles, depicted in light blue, are simple CES bundles of the different components.

Each non-CO_2 greenhouse gas (CH_4, N_2O, and fluorinated gases FGAS) enters the production function as a component of production: their value is calibrated at the level of CO_2-equivalent emissions they generate and an arbitrarily small price. The elasticity of substitution is chosen following Hyman et al. (2003) and represents the different abatement costs corresponding to the greenhouse gas.

Fossil energy production differs from the standard nesting to avoid unrealistic substitutions, for instance, the replacement of oil by coal or gas in the production of refined petroleum. In this dedicated nesting, the fuel-specific resource is of two different types:

- This is the natural resource $NatRes$ in the case of primary fossil energy production (coal, oil, gas).
- This is crude oil in the case of petroleum and coal products.

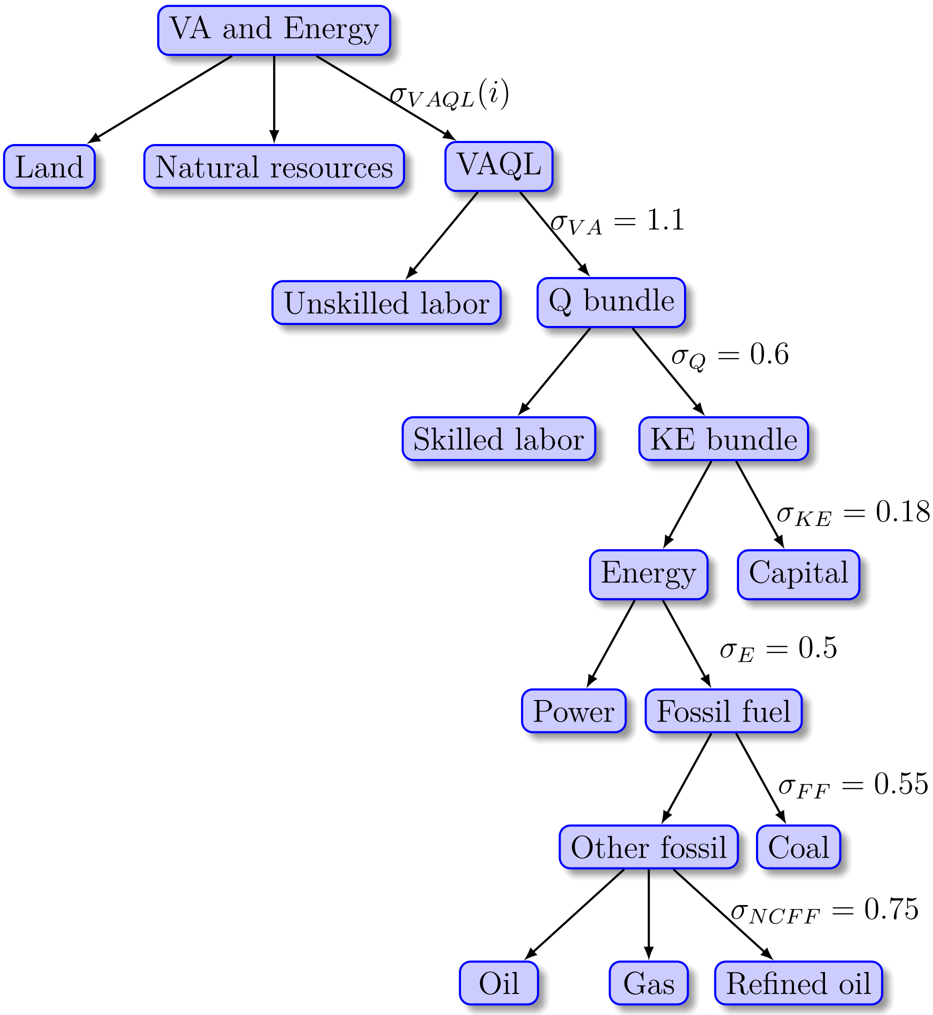


Figure 5: Value added and energy nesting

Value-added and energy

The value-added and energy bundle is almost identical across sectors in MIRAGE, given that energy in value added is toggled (and aggregation meets the requirements of separating the five energy goods). The associated nesting is shown in Fig. 5. This choice to put energy in the same bundle as capital instead of considering it as an intermediate input is classic in the CGE literature—see, for instance, Burniaux and Truong (2002). The rationale is the link between capital and energy complementarity: for a given energy efficiency, the higher the use of capital, the more energy it requires to produce output. Notice also the difference between coal and other fossil fuels: in the production processes, it is often easier to substitute gas with oil, rather than coal, hence the two-layer nesting.

The only sectors that do not share this exact nesting are refined oil production and fossil electricity sectors. In this case, the associated fossil fuel required for production is placed higher in the production function, with a Leontief structure to account for the non-substitutable nature of this input (see Fig. 4), and hence does not appear in the VA

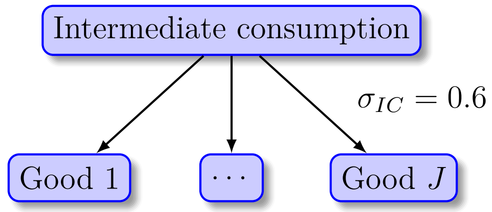


Figure 6: Intermediate consumption nesting

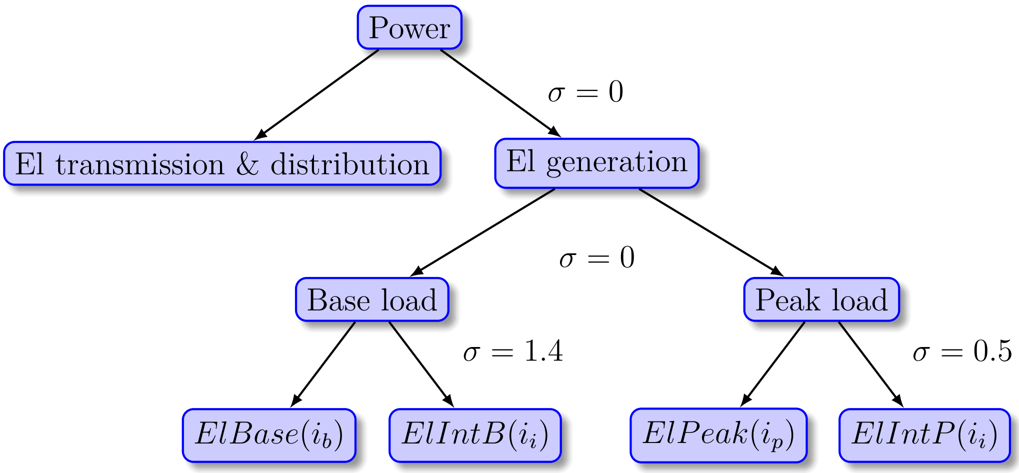


Figure 7: Power production nesting

and energy bundle. Apart from this slight difference, the rest is identical.

Intermediate consumption

Intermediate consumption is identical across sectors, as illustrated in Fig. 6. The demand for good by origin is presented in Section 2.4.

2.3 Power supply

Power (the aggregate electricity commodity) is generated from multiple sources, including renewables, nuclear, coal, oil, and gas. The regional power producer provides electricity for firms and households. Electricity as such can also be traded—meaning that the utility can export or import aggregate electricity, indifferently coming from the different generation sources.

2.3.1 Electricity activity demand

Power production in region r follows the nesting structure given in Fig. 7. The demand for electricity activities in region r is only from the power producer in region r. Lower-level electricity activities are not traded.

Electricity generation is divided between baseload and peak load production. A Leontief production function has been chosen to account for (almost) no storage capacities of electricity. This elasticity can be increased to simulate scenarios where storage capacities become important enough to allow substitution between baseload and peak production. Then, the nesting tries to model the merit order curve:

- Baseload production comes from pure baseload electricity $ElBase_{i_brt}$, and base intermittent electricity $ElIntB_{i_irt}$. Pure baseload electricity is composed of sectors $i_b \in EL\_BL$ which are always considered as baseload sectors. By default, it includes coal, nuclear, and baseload hydroelectricity. Coal and nuclear are easy to understand because they are always at the very bottom of the merit order curve due to their low variable costs. Renewables also have low variable costs, but they are either intermittent (e.g., wind and solar) or in limited availability (e.g., hydro). For this reason, hydroelectricity is split between baseload and peak load hydroelectricity, while intermittent electricity sectors indexed by $i_i \in EL\_INT$ are distributed between a baseload production $ElIntB_{i_irt}$ and a peak load production $ElIntP_{i_irt}$. More explanations on this distribution are given below.
- Peak load production comes from pure peak load electricity, $ElPeak_{i_prt}$, and peak intermittent electricity, $ElIntP_{i_irt}$. By default, pure peak load sectors $i_p \in EL\_PL$ are gas, oil, and peak load hydroelectricity. Gas and oil are the last plants to be called on the merit order curve because of their relatively high variable costs. Peak renewable electricity activities are the counterpart of baseload renewable electricity discussed above.
- The elasticities of substitution inside each nest follow from Peters (2016).

Distribution of intermittent renewables

Intermittent electricity production[2] addresses both the demand for baseload and peak intermittent electricity. More precisely, each intermittent electricity sector i_i gets a baseload contribution $ElIntB_{i_irt}$ and a peak load contribution $ElIntP_{i_irt}$. It is assumed that intermittent electricity is produced randomly without any correlation to electricity demand. Thus, the proportion of supply that is allocated to baseload electricity is a fixed parameter r_r^{ElB} that depends on the region r. This ratio is calibrated by evaluating the ratio of all baseload electricity production—except intermittent renewables—to total electricity generation; then, intermittent renewables are distributed according to this ratio in order to mimic their uncorrelated production:

$$ElIntB_{i_irt} = r_r^{ElB} Y_{i_irt}\,, \quad ElIntP_{i_irt} = (1 - r_r^{ElB}) Y_{i_irt}\,, \quad \text{for } i_i \in EL\_INT\,. \tag{5}$$

[2] In most cases, this concerns wind and solar, but it is possible to assign any sector to this category in the aggregation procedure.

The prices are determined so as to enforce these conditions. Indeed, from the usual CES equations, we know that

$$ElIntB_{i_irt} = a_{i_ir}^{ElIntB} ElB_{rt} \left(\frac{P_{rt}^{ElB}}{P_{i_irt}^{ElIntB}} \right)^{\sigma^{ElB}} , \tag{6}$$

where σ^{ElB} the elasticity of substitution in the baseload electricity nest. Inverting this equation and replacing $ElIntB_{i_irt}$ by $r_r^{ElB} Y_{i_irt}$, we obtain

$$P_{i_irt}^{ElIntB} = P_{rt}^{ElB} \left(\frac{a_{i_ir}^{ElIntB} ElB_{rt}}{r_r^{ElB} Y_{i_irt}} \right)^{1/\sigma^{ElB}} . \tag{7}$$

Next, supply value equals demand value implies that

$$(1 + tax_{i_irt}^{P}) P_{i_irt}^{Y} Y_{i_irt} = P_{i_irt}^{ElIntB} ElIntB_{i_irt} + P_{i_irt}^{ElIntP} ElIntP_{i_irt} , \tag{8}$$

where $tax_{i_irt}^{P}$ is the production tax. Replacing $ElIntB_{i_irt}$ and $ElIntP_{i_irt}$ by $r_r^{ElB} Y_{i_irt}$ and $(1 - r_r^{ElB}) Y_{i_irt}$ allows determining the last price

$$P_{i_irt}^{ElIntP} = \frac{(1 + tax_{i_irt}^{P}) P_{i_irt}^{Y} - r_r^{ElB} P_{i_irt}^{ElIntB}}{1 - r_r^{ElB}} . \tag{9}$$

Distribution of hydroelectricity

The distribution of hydroelectricity between baseload and peak load follows from the GTAP database.

2.3.2 Electricity activity supply

The production of electricity activities follows either from the standard MIRAGE function (see Fig. 2), or the fossil electricity function (see Fig. 4).

2.4 Trade

2.4.1 Trade and domestic demand

Final demand, intermediate demand and capital good demand are aggregated to form total demand Dem_{ist}^{TOT}:

$$Dem_{ist}^{\text{TOT}} = C_{ist} + \sum_j IC_{ijst} + KG_{ist} . \tag{10}$$

By default, the regional demand in MIRAGE uses a standard Armington-type specification using CES functions, with a home bias: it is easier to switch between imports of different

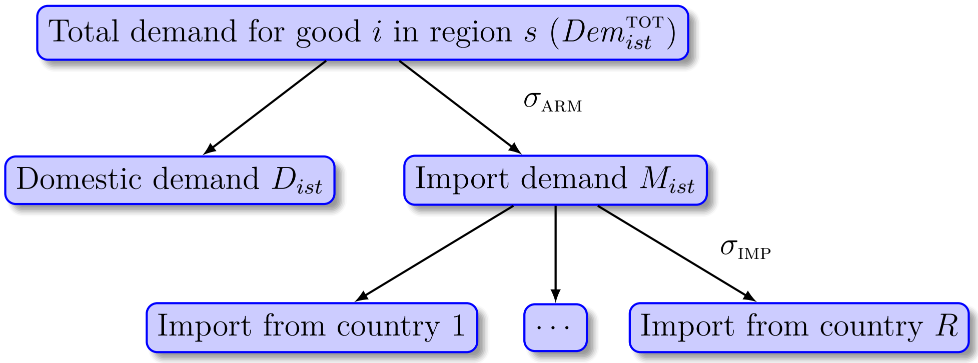


Figure 8: Demand nesting for good i

origins than between domestic production and imports. Such a specification is depicted in Fig. 8. For future reference, we denote by D_{ist} the domestic demand of good i in region s, while Dem_{irst} is the demand for imported goods from r to s. Finally, the value of Armington elasticity of substitution of imports from different regions σ_{IMP} is sourced from Fontagné, Guimbard, et al. (2022) for goods and from the GTAP database for services. Armington elasticity of substitution of domestic and foreign demand will follow the $\sqrt{2}$ rule:

$$\sigma_{\text{lower lvl}} - 1 = \sqrt{2}(\sigma_{\text{higher lvl}} - 1)\,.$$

2.4.2 Trade costs

Price of demand for imported goods i from region r to s, P^{DEM}_{irst}, is usually higher than the production price of domestic goods in region r, due to the existence of trade costs. These trade costs are of three different types in MIRAGE:

- Tariffs
- Ad valorem equivalents of non-tariff measures (NTM)
- Purchasing of international transportation services

In general, production prices in region r for exports to s are denoted P^{PROD}_{irst}. They incorporate the iceberg trade cost $tCost_{irst}$ to the production cost. Next, the price before boarding is denoted P^{FOB}_{irst}, and incorporate export tax and all the NTM related to exports. Then, the price after transportation is P^{CIF}_{irst}. Finally, the price of demand P^{DEM}_{irst} adds the tariff costs to the CIF price.

Non-tariff measures (NTM)

Using NTM_{irst} as an *ad valorem* equivalent for NTM, the latter can either be modeled as:

- an iceberg trade cost, $shareNTM^{tCost}_{irs} NTM_{irst}$,
- an export-tax equivalent (rent-generating), $shareNTM^{tax^{\text{EXP}}}_{irs} NTM_{irst}$,

- an import-tax equivalent (rent-generating), $shareNTM_{irs}^{Tariff} NTM_{irst}$.

By default, without specific knowledge about the best modeling assumptions, NTM are assumed to be 1/3 iceberg, 1/3 export-tax equivalent, and 1/3 import-tax equivalent. In other words, we use by default

$$shareNTM_{irs}^{tCost} = shareNTM_{irs}^{tax^{\text{EXP}}} = shareNTM_{irs}^{Tariff} = 1/3.$$

In every region, the rents created by import-tax equivalent NTM on imports and export-tax equivalents on exports are allocated to the representative household by a lump-sum transfer. It should also be noted that the *ad valorem* equivalent for protection in services, tax_{irst}^{SER}, is implemented at this stage as NTM related to the iceberg trade cost share.

MIRAGE only uses information on the trade-restrictiveness of NTM (no positive effects are considered, such as those arising from increased trust between the consumers of trading countries), using *ad valorem* equivalents from Fontagné, Mitaritonna, et al. (2016) for services and Kee et al. (2009) for goods.

Generalized trade costs

In order to adopt a more compact formalism, useful for exposition, the different trade costs are aggregated using "generalized" tariffs $GnTrf_{irst}$, export taxes $GnTax_{irst}^{\text{EXP}}$, and iceberg trade costs $GnTC_{irst}$. By using the notations $Tariff_{irst}$ for tariffs, tax_{irst}^{EXP} for export taxes and tax_{irst}^{MFA} for export taxes equivalent to multi-fiber arrangement (MFA) quotas, we obtain the following relations between generalized trade costs and the original parameters:

$$\begin{aligned} GnTC_{irst} &= 1 + tCost_{irst} + shareNTM_{irs}^{tCost} \left(tax_{irst}^{\text{SER}} + NTM_{irst} \right) , \\ GnTrf_{irst} &= Tariff_{irst} + shareNTM_{irs}^{Tariff} NTM_{irst} , \\ GnTax_{irst}^{\text{EXP}} &= tax_{irst}^{\text{EXP}} + tax_{irst}^{\text{MFA}} + shareNTM^{tax_{irs}^{\text{EXP}}} NTM_{irst} . \end{aligned} \tag{11}$$

Despite this aggregation, any trade policy scenario has to be implemented directly on $Tariff_{i,r,s,t}$, $tCost_{irst}$, NTM_{irst}, tax_{irst}^{SER}, and tax_{irst}^{EXP}.

Transport costs

The transport sector is covered in Section 2.6. For the moment, we just need to know that $\mu_{irs} P_{irst}^{Tr}$ is the price to transport a unit value of good i from r to s.

2.4.3 Good market

The equilibrium in the goods market determines the equilibrium price of goods. To be consistent with everything said above, the production of good i in region r equals the sum of domestic demand for good i and total export of good i from region r:[3]

$$Y_{irt} = D_{irt} + \sum_s GnTC_{irst} Dem_{irst} . \tag{12}$$

The presence of the generalized trade cost in front of the export goods demand is easy to understand: since the generalized trade costs are iceberg costs, the quantity shipped should be higher than the quantity received by a factor equal to the trade cost.

Next, denoting by $GnMC_{irt}$ the "generalized marginal cost" that encapsulates imperfect competition (see Section 2.5), the production price can be written

$$P^{\text{PROD}}_{irst} = P^{Y}_{ir} GnMC_{irt} GnTC_{irst} \left(1 + tax^{P}_{irt}\right) , \tag{13}$$

where P^{Y}_{ir} is the unit production cost and tax^{P}_{irt} is the production tax. As explained above, FOB price is the production price plus export tax:

$$P^{\text{FOB}}_{irst} = P^{\text{PROD}}_{irst} \left(1 + GnTax^{\text{EXP}}_{irst}\right) . \tag{14}$$

Keeping the same spirit, CIF prices are FOB prices plus the cost of transportation:

$$P^{\text{CIF}}_{irst} = P^{\text{FOB}}_{irst} + GnMC_{irt} GnTC_{irst} \mu_{irs} P^{Tr}_{irst} . \tag{15}$$

$GnMC_{irt}$ is placed in front of the transport price following the derivation of Section 2.5: since the transport price is applied for each variety, it is affected by the same markup as the FOB price. As for the term $GnTC_{irst}$, it can be seen as a contribution that increases the transport price when iceberg trade costs rise. Finally, import prices are CIF prices plus import tariffs:

$$P^{\text{DEM}}_{irst} = P^{\text{CIF}}_{irst} \left(1 + GnTrf_{irst}\right) . \tag{16}$$

2.5 Imperfect competition

MIRAGE implementation of imperfect competition à la Krugman (1979) is inspired by two contributions: Balistreri and Rutherford (2013) for the theoretical derivation calibration procedure and Bekkers and Francois (2018) for implementation through "generalized marginal cost".

In a nutshell, we define generalized marginal cost $GnMC_{irt}$ as:

$$GnMC_{irt} = \begin{cases} 1 & \text{in perfect competition} \\ N_{irt}^{1/(1-\sigma_{\text{VAR}})} \left[\sigma_{\text{VAR}}/(\sigma_{\text{VAR}} - 1)\right] & \text{in imperfect competition} \end{cases} \tag{17}$$

[3] In this section, we leave aside the transport sectors, which are a bit peculiar due to the presence of freight supply (see Section 2.6). In this regard, the equations in this section should be understood as valid for all i except the transport sectors.

Then, the expression of imperfect competition in MIRAGE is very similar to the perfect competition framework.

2.5.1 Theoretical setup

The Krugman model is characterized by a love of variety, which is materialized in the demand CES functions:

$$\begin{cases} D_{ist} &= \left[\int_{\Omega} \left(\tilde{D}_{\omega ist} \right)^{\frac{\sigma_{\text{VAR}}-1}{\sigma_{\text{VAR}}}} \mathrm{d}\omega \right]^{\frac{\sigma_{\text{VAR}}}{\sigma_{\text{VAR}}-1}}, \\ Dem_{irs} &= \left[\int_{\Omega} \left(\tilde{Dem}_{\omega irst} \right)^{\frac{\sigma_{\text{VAR}}-1}{\sigma_{\text{VAR}}}} \mathrm{d}\omega \right]^{\frac{\sigma_{\text{VAR}}}{\sigma_{\text{VAR}}-1}}. \end{cases} \tag{18}$$

Here, tilde variables are associated with varieties, which are indexed by ω. σ_{VAR} is the elasticity of substitution between varieties. If $\tilde{P}^{\text{DEM}}_{\omega irst}$ is the price paid by the consumer in s for a variety ω, then the aggregate expense is

$$\int_{\Omega} \tilde{P}^{\text{DEM}}_{\omega irst} \tilde{Dem}_{\omega irst} \, \mathrm{d}\omega \, .$$

Maximizing this program gives the FOC demand equation

$$\tilde{P}^{\text{DEM}}_{\omega irst} = \left(\frac{Dem_{irst}}{\tilde{Dem}_{\omega irst}} \right)^{1/\sigma_{\text{VAR}}}, \tag{19}$$

hence the derivative

$$\frac{\partial \tilde{P}^{\text{DEM}}_{\omega irst}}{\partial \tilde{Dem}_{\omega irst}} = -\frac{1}{\sigma_{\text{VAR}}} \left(\frac{\tilde{P}^{\text{DEM}}_{\omega irst}}{\tilde{Dem}_{\omega irst}} \right). \tag{20}$$

On the supply side, each variety is produced by a monopolistic firm. Let us define the production price of a variety as $\tilde{P}^{\text{PROD}}_{\omega irst} = m_{\omega irst} GnTC_{irst} P^{Y}_{irt}$, where $m_{\omega irst}$ is the markup over marginal cost. The profit for one firm on one market can be expressed as:

$$\tilde{\pi}_{\omega irst} = \tilde{P}^{\text{PROD}}_{\omega irst} \tilde{Dem}_{\omega irst} - GnTC_{irst} P^{Y}_{irt} \tilde{Dem}_{\omega irst} \, . \tag{21}$$

Maximizing this profit gives the FOC supply equation

$$\frac{\partial \tilde{\pi}_{\omega irst}}{\partial \tilde{Dem}_{\omega irst}} = \tilde{P}^{\text{PROD}}_{\omega irst} + \tilde{Dem}_{\omega irst} \frac{\partial \tilde{P}^{\text{PROD}}_{\omega irst}}{\partial \tilde{Dem}_{\omega irst}} - GnTC_{irst} P^{Y}_{irt} = 0 \, . \tag{22}$$

Markup

If we rewrite this expression from the demand side point of view, we need to use $\tilde{P}^{\text{DEM}}_{\omega irst}$ instead of $\tilde{P}^{\text{PROD}}_{\omega irst}$. The correspondence between both is:

$$\tilde{P}^{\text{PROD}}_{\omega irst} = \frac{1}{(1 + tax^P_{irt})(1 + GnTax^{\text{EXP}}_{irst})} \left[\frac{\tilde{P}^{\text{DEM}}_{\omega irst}}{(1 + GnTrf_{irst})} - GnTC_{irst} \mu_{irs} P^{Tr}_{irst} \right] . \tag{23}$$

And in derivatives:

$$\frac{\partial \tilde{P}^{\text{PROD}}_{\omega irst}}{\partial \tilde{Dem}_{\omega irst}} = \frac{1}{(1 + GnTrf_{irst})(1 + tax^P_{irt})(1 + GnTax^{\text{EXP}}_{irst})} \frac{\partial \tilde{P}^{\text{DEM}}_{\omega irst}}{\partial \tilde{Dem}_{\omega irst}} .$$

Injecting Eq. (20) yields the full expression

$$\begin{aligned} \tilde{P}^{\text{DEM}}_{\omega irst} = & \frac{\sigma_{\text{VAR}}}{\sigma_{\text{VAR}} - 1} (1 + GnTrf_{irst}) GnTC_{irst} \\ & \times \left[(1 + tax^P_{irst})(1 + GnTax^{\text{EXP}}_{irst}) P^Y_{irt} + \mu_{irs} P^{Tr}_{irst} \right] . \end{aligned} \tag{24}$$

By identification with Eq. (16), the markup is:

$$m_{irst} = \frac{\sigma_{\text{VAR}}}{\sigma_{\text{VAR}} - 1} . \tag{25}$$

Aggregation

Because demand and prices are the same for all varieties, the aggregate demand is simply

$$Dem_{irst} = \tilde{Dem}_{\omega irst} N_{irt}^{\sigma_{\text{VAR}}/(\sigma_{\text{VAR}} - 1)} , \tag{26}$$

where $N_{irt} = \int_\Omega \mathrm{d}\omega$ is the "volume" of varieties. The aggregate price being such that

$$P^{\text{DEM}}_{irst} Dem_{irst} = \int_\Omega \tilde{P}^{\text{DEM}}_{\omega irst} \tilde{Dem}_{\omega irst} \, \mathrm{d}\omega ,$$

it follows that

$$P^{\text{DEM}}_{irst} = \tilde{P}^{\text{DEM}}_{\omega irst} N_{irt}^{1/(1 - \sigma_{\text{VAR}})} . \tag{27}$$

Hence, we can write:

$$\begin{aligned} P^{\text{DEM}}_{irs} = N_{irt}^{1/(1 - \sigma_{\text{VAR}})} & \frac{\sigma_{\text{VAR}}}{\sigma_{\text{VAR}} - 1} (1 + GnTrf_{irst}) \, GnTC_{irst} \\ & \times \left[\left(1 + tax^P_{irst} \right) (1 + GnTax^{\text{EXP}}_{irst}) \, P^Y_{irt} + \mu_{irs} P^{Tr}_{irst} \right] . \end{aligned} \tag{28}$$

2.5.2 Generalized marginal cost

We define $GnMC_{ist}$ after Bekkers and Francois (2018) as the generalized marginal cost of producing good i in region s. As such, domestic prices can be written

$$P_{ist}^{D} = GnMC_{ist} P_{ist}^{Y} \left(1 + tax_{ist}^{P}\right) , \tag{29}$$

while export prices read

$$P_{irst}^{\text{DEM}} = GnMC_{irt}(1 + GnTrf_{irst}) GnTC_{irst} \left[\left(1 + tax_{irt}^{P}\right)(1 + GnTax_{irst}^{\text{EXP}}) P_{irt}^{Y} + \mu_{irs} P_{irst}^{Tr}\right] . \tag{30}$$

As a consequence, in the Krugman case, we can identify

$$GnMC_{irt} = N_{irt}^{\frac{1}{1-\sigma_{\text{VAR}}}} \frac{\sigma_{\text{VAR}}}{\sigma_{\text{VAR}} - 1} . \tag{31}$$

Because of free entries, zero-profit condition must hold. Therefore, the profit must cover exactly the fixed cost per variety $\tilde{fc}$ such that

$$(m_{irst} - 1) GnTC_{irst} \tilde{Dem}_{\omega irst} = \tilde{fc}_{irs} . \tag{32}$$

Total fixed cost is the integral over all varieties, summed over all export regions (including the domestic region). Because production is equal to domestic demand plus exports, i.e.

$$Y_{irt} = D_{irt} + \sum_{s} GnTC_{irst} Dem_{irst} ,$$

then total fixed cost is equal to

$$fc_{ir} = \frac{Y_{irt}}{\sigma_{\text{VAR}} - 1} N_{irt}^{\frac{1}{1-\sigma_{\text{VAR}}}} . \tag{33}$$

This is the reason why imperfect competition is represented by a marginal cost: fixed costs are proportional to output since the number of firms adapts to respect the zero-profit condition.

2.6 International transportation

The transport sectors play a specific role: they cover both regular transport activities, which are demanded and can be traded like any other service, and international transport of goods. The latter accounts for the difference between FOB and CIF values of traded goods. Thus, the market clearing equation for a transport sector presents two terms: the demand for transport activities other than freight, and freight. In equation, denoting by

TrT the subset of transport sectors, it reads

$$Y_{jrt} = \underbrace{D_{jrt} + \sum_s Dem_{jrst}}_{\text{Regular transport activities}} + \underbrace{Tr^{\text{Supply}}_{jrt}}_{\text{Freight}}, \quad j \in TrT\,. \tag{34}$$

The transport sectors *need to be considered as perfectly competitive* with constant returns to scale. In MIRAGE, transport demand for a good i is first decomposed between demand for the various transport sectors—also called "modes". Then, each transport sector demand is addressed by a supply aggregated at world level. Thus, there are two different "aggregation" processes that should not be confused: aggregation of transport modes j in the demand side, and aggregation of transport producing regions r in the supply side. The two following sections delve into the modeling of the supply and demand for international transport of goods.

2.6.1 Transport demand

In order to determine transport demand, we can use Eq. (16) and decompose final import value into production prices and trade costs:

$$P^{\text{DEM}}_{irst} Dem_{irst} = (1 + GnTrf_{irst}) \left(P^{\text{FOB}}_{irst} + GnMC_{irt} GnTC_{irst} \mu_{irs} P^{Tr}_{irst} \right) Dem_{irst}\,.$$

By identification, transport value is equal to the second part of the right-hand side without tariffs, so that transport demand reads

$$Tr_{irst} = \mu_{irs} GnTC_{irst} GnMC_{irt} Dem_{irst}\,. \tag{35}$$

With this equation, we can finally interpret the parameter μ_{irs} as the conversion factor between traded quantities (Dem_{irst}) and the transport demand they require to be traded (Tr_{irst}). The freight demand is then broken down by modes $\tilde{T}r$ indexed by j, through a Cobb–Douglas specification:

$$\tilde{T}r_{jirst} = a^{Tr}_{jirs} Tr_{irst} \frac{P^{Tr}_{irst}}{P^{\tilde{T}r}_{jt}}, \quad j \in TrT\,. \tag{36}$$

It should be understood that each mode corresponds to a transport sector (be it water, air or miscellanesous transport sectors in GTAP database); as indicated above, j is an index that runs over the subset of transport sectors, denoted TrT. Then, transportation price for a given route is defined as a Cobb–Douglas aggregate price:

$$P^{Tr}_{irst} = \prod_{j \in TrT} {P^{\tilde{T}r}_{jt}}^{a^{Tr}_{jirs}}\,. \tag{37}$$

2.6.2 Transport supply

Each region contributes to the world supply of freight. The supply is addressed for each transport mode $j \in TrT$, and the choice between the various transport exporters is made according to a Cobb–Douglas demand function:

$$Tr_{jrt}^{\text{Supply}} = a_{jr}^{Tr^{\text{Supply}}}\, World_{jt}^{Tr} \frac{P_{jt}^{Tr^{\text{Mode}}}}{P_{jrt}^{Y}\left(1 + tax_{jr}^{P}\right)} \,. \tag{38}$$

These supplies are aggregated in a world supply of freight per mode:

$$World_{jt}^{Tr} = c_{j}^{Tr} \prod_{r} Tr_{jrt}^{\text{Supply}^{a_{jr}^{Tr^{\text{Supply}}}}} \,. \tag{39}$$

Finally, supply is connected to demand at world level:

$$World_{jt}^{Tr} = \sum_{irs} \tilde{T}r_{jirst} \,. \tag{40}$$

2.7 Capital and investment dynamics

Investment in a given region is a bundle obtained using the same CES nesting structure as for intermediate consumption. The mobility of capital only comes from depreciation, combined with the allocation of new investments. This confers on investment an important role as the only adjustment device for capital stock. This "putty-clay" hypothesis is important because it implies that capital stock adjusts gradually. The sectoral allocation of capital can thus be suboptimal, and the corresponding loss can be interpreted as an adjustment cost for the economy. In addition, these assumptions imply that the rate of return on capital varies across sectors after the initial year.

2.7.1 Investment allocation

Foreign direct investments (FDI) are not explicitly considered in Mirage, though they are embodied implicitly in the current account (taken from EconMap). In practice, a single generic formalization encompassing both domestic and foreign investment is used, though only the domestic r, r elements are used. This leaves the possibility to update the outdated version that included explicit FDI. Investment level is a function of the initial savings pattern, the present capital stock, and the sectoral rate of return to capital, with an elasticity α. Hence, investment by region r in s can be written

$$Inv_{irst} = B_{rt} a_{irs} Capital_{ist} \exp\left[\alpha\left(\frac{W_{ist}^{Capital}}{P_{st}^{InvTOT}} - \delta_r\right)\right] \,. \tag{41}$$

In this equation, $Capital_{ist}$ is the capital stock, $W_{ist}^{Capital}$ is the sectoral rate of return,[4] δ_r is the depreciation rate, P_{st}^{InvTOT} is the price of total investment in region s, and B_{rt} is a scale coefficient for investments by region r (to be fixed by imposing the current account equation). Total investment in region s is, of course,

$$Inv_{st}^{\mathrm{TOT}} = \sum_{i,r} Inv_{irst} \,. \tag{42}$$

The capital stock being dynamics, it evolves each year following the equation

$$K_{irst} = K_{irs,t-1}(1 - \delta_r) + Inv_{irst} \,, \tag{43}$$

where K_{irst} is the capital stock invested by r in s, so that total capital is

$$Capital_{ist} = \sum_{r} K_{irst} \,. \tag{44}$$

Finally, the closure of investment allocation is obtained through the current account equation (see Eq. (48)):

$$Sav_{st} Rev_{st} = \sum_{i,r} P_{st}^{InvTOT} Inv_{irst} + WGDP_t \cdot CA_{st} \,,$$

where CA_{st} is the current account surplus for region s, Rev_{st} is the total revenue of region s, Sav_{st} is its saving rate, and $WGDP_t$ is world GDP.

2.7.2 Capital goods

Total investment is made up of capital goods KG_{irt}, following a CES specification:

$$KG_{irt} = a_{ir}^{KG} Inv_{rt}^{\mathrm{TOT}} \left(\frac{P_{r,t}^{InvTOT}}{P_{irt}^{KG}} \right)^{\sigma_{KG}} \,, \tag{45}$$

$$P_{rt}^{InvTOT} Inv_{rt}^{\mathrm{TOT}} = \sum_{i} P_{irt}^{KG} KG_{irt} \,, \tag{46}$$

and capital goods are subject to a specific taxation:

$$P_{irt}^{KG} = P_{irt}^{DemTOT} \left(1 + tax_{irt}^{KG} \right) \,. \tag{47}$$

[4] In the static version of the model, perfect mobility of capital implies this sectoral rate of return to be equal to the regional rate of return. In the dynamic version, the variation in rates of return between the different sectors plays a key role in the reallocation of capital from one period to the next.

2.8 Macroeconomic closure and revenue

2.8.1 Income and tax revenues

As a general equilibrium model, MIRAGE needs to compute tax revenues and recycle them into income, either for consumption or savings. Since there is only one representative agent per region, tax revenue is distributed as a lump-sum transfer. Tax income incorporates the following revenues:

- Production tax revenues (a share of production costs),
- Export tax revenues (comprises the export tax tax^{EXP}_{irst} and the tax equivalent to MFA quotas tax^{MFA}_{irst}),
- Tariff revenues (a share of CIF values),
- Rents from NTM (see Section 2.4 for details),
- Consumption tax revenue (comprises final consumption tax, intermediate consumption tax, tax on capital goods, and tax on intermediate energy goods),
- GHG tax revenue (carbon tax equivalent to carbon market).

Total revenue Rev_{rt} of region r is the sum of the five factors income and of tax revenue. This revenue is then divided between consumption and savings, with a saving rate Sav_{rt} coming from EconMap.

2.8.2 Macroeconomic closure

Adjustments in exports and imports relative to price changes induce pressure to adjust the trade balance. We consider that the trade balance follows long-term macroeconomic drivers and is not affected by counterfactual shocks. This closure implies that the real exchange rate adjusts to maintain the trade balance, which changes export competitiveness and import buying capacity. In this framework, the current account balance is determined dynamically by MaGE,[5] and is then fixed in MIRAGE at its value as a share of world GDP:

$$Sav_{st} Rev_{st} = \sum_{i,r} P^{InvTOT}_{st} Inv_{irst} + WGDP_t \cdot CA_{st} \,. \tag{48}$$

As indicated previously, savings Sav_{st}, as well as the current account balance CA_{st}, both come from EconMap (see Section 4 for details).

2.9 Energy, GHG emissions, and mitigation policies

MIRAGE considers the consumption of five energy goods: electricity, coal, oil, gas, and refined petroleum. As explained in Section 2.2, energy demand for firms is in the same

[5] In MaGE, the current account balance is a function of demography, life-cycle of savings, and so forth, given that current account imbalances sum to zero globally.

bundle as capital, in the value-added structure instead of intermediate consumption. Moreover, fossil production and fossil electricity sectors possess a nesting that differs from the standard MIRAGE nesting, in order to prevent unrealistic substitutions.

This section describes how energy efficiency enters the model and how *physical* quantities of energy are accounted for to evaluate GHG emissions properly. Finally, it introduces how GHG mitigation policies are implemented in the model.

2.9.1 Energy efficiency

The value of aggregate energy in sector j in country r, E^{TOT}_{jrt}, is subject to productivity improvements, EE_{jrt}, based on the growth model.[6] These productivity improvements are introduced at the capital–energy bundle level, KE_{jrt}:

$$E^{\text{TOT}}_{jrt} = a_E EE_{jrt} KE_{jrt} \left(\frac{P^{KE}_{jrt}}{P^{E}_{jrt}} \right)^{\sigma_{KE}} . \tag{49}$$

2.9.2 Energy accounting

Using CES functional forms with variables in monetary units leads to inconsistencies when trying to retrieve physical quantities. In our case, this matters for energy consumption, production and trade, and their consequences for GHG emissions (preliminary simulations of MIRAGE showed that there could be a gap of more than 20% between a country's energy consumption and energy demanded if proportionality was assumed between monetary and physical values). Therefore, in addition to accounting relations in constant dollars, MIRAGE integrates a parallel accounting in energy physical quantities (in million tons of oil equivalent, Mtoe) allowing GHG emissions to be computed (in million tons of carbon dioxide, $MtCO_2$). Since the CES architecture does not maintain coherence in physical quantities, MIRAGE introduces energy- and country-specific adjustment coefficients. These two aggregation coefficients allow our basic energy accounting relationships to remain valid. This means that, if e is an index that runs over energy types, the quantity produced by one country E^Y_{ert} must equal the demand in this country both local, E^D_{ert}, and from abroad, E^{Dem}_{erst}; and energy consumption (by households, E^C_{est} and firms, E^{EIC}_{ejst}) in one country must equal its local and foreign demand.

$$E^Y_{ert} = E^D_{ert} + \sum_s E^{Dem}_{erst} , \tag{50}$$

$$E^C_{est} + \sum_j E^{EIC}_{ejst} = E^D_{est} + \sum_r E^{Dem}_{erst} . \tag{51}$$

The corresponding adjustment coefficient, $AgDem_{ert}$ (resp. AgC_{ert}) rescales a country's

[6]There are three factors in MAGE, capital, labor, and energy. To these factors are associated two shifters of productivity, one of them being the energy efficiency B_{rt}, which is directly related to EE_{jrt}.

demand (resp. consumption) such that it matches the physical quantities produced (resp. demanded). In turn, only the energy quantity produced is proportional to the production volume Y due to it being above rather than inside the CES. The epsilons in Eq. (52) are constant conversion coefficients calibrated from the energy quantity data; they allow for linking energy quantities with corresponding volumes of demand for local goods, D_{ert}, bilateral demand, Dem_{ert}, local final consumption, C_{est}, and local intermediate consumption, E^{IC}_{ejst}.

$$\begin{aligned}
E^{Y}_{ert} &= \epsilon^{Y}_{er} YtoVol_{ert} Y_{ert} \,, \\
E^{D}_{ert} &= \epsilon^{D}_{er} AgDem_{ert} YtoVol_{ert} D_{ert} \,, \\
E^{Dem}_{erst} &= \epsilon^{Dem}_{ers} AgDem_{ert} YtoVol_{ert} Dem_{erst} \,, \\
E^{C}_{est} &= \epsilon^{C}_{es} AgC_{est} C_{est} \,, \\
E^{IC}_{ejst} &= \epsilon^{IC}_{ejs} AgC_{est} \left(EIC_{ejst} + IC_{ejst} \right) \,.
\end{aligned} \tag{52}$$

2.9.3 GHG emissions

In general, greenhouse gases of different types are indexed by g. In the model, emissions occur at three different levels:

- Final consumption of energy goods e, $EmGHG^{C}_{gert}$ (all GHG gases)
- Intermediate consumption of energy goods e by sector i, $EmGHG^{IC}_{geirt}$ (only CO_2)
- Emissions related to production process of sector i, $EmGHG^{Y}_{girt}$ (all GHG gases)

Emissions associated with energy consumption are recovered in proportion to the quantities of energy consumed, using energy-, sector-, and country-specific factors determined by the data. This means that the accounting correction coefficient applies to these emissions. On the other hand, other GHG emissions which enter directly the production function and are left as-is.

Emissions from international transportation are allocated to international freight proportionally:

$$EmGHG^{\text{Freight}}_{g,TrT,r,t} = \left[\sum_{i} EmGHG^{IC}_{g,i,TrT,r,t} + EmGHG^{Y}_{g,TrT,r,t} \right] \frac{Tr^{\text{Supply}}_{TrT,r,t}}{Y_{TrT,r,t}} \,. \tag{53}$$

These emissions can enter the emission reduction policy or not, depending on whether the sector is listed in the `InternationalFreight` set. In this case, $EmGHG^{\text{Freight}}$ is computed, but not added to carbon market emissions and not subject to carbon taxation.

2.9.4 GHG mitigation policies

The implementation of GHG mitigation policies in Mirage is based on the work presented in Bellora and Fontagné (2023). Basically, it relies on an equivalent tax on GHG emissions, which captures the shadow price of all policy instruments, whether they are regulatory or market-based. The level of this tax is either calculated at each time period to respect the emission target or is exogenous. Therefore, a policy scenario consists of setting an emission target (or an exogenous tax) on each country, based on what is assumed to be their commitments (for instance, whether they respect the Paris Agreement or not).

Particular attention is paid to the European Emission Trading System (EU ETS). To model this carbon market, a separate tax is calculated for industries participating in this market, requiring these sectors to decrease their emissions up to a given target (the reference scenario is the Fit for 55 package, namely a decrease of 61% in 2030 with respect to 2005). Free allowances are also allocated to ETS sectors exposed to international competition and need to be taken into account in the model, with a possible phasing out that depends on the scenario.

More specifically, without free allowances, the equivalent tax on emission of gas g, tax^{GHG}_{grt}, is applied directly to the different prices:

$$P^{C}_{ert} = P^{DemTOT}_{ert}\left(1 + tax^{C}_{ert}\right) + \sum_{g} tax^{GHG}_{grt} AgC_{ert} EmF^{C}_{ger} P^{U}_{rt}\,, \tag{54}$$

$$P^{GHG}_{girt} = \begin{cases} \left(1 + tax^{GHG}_{grt} EmF^{Y}_{gir}\right) P^{U}_{rt}\,, & \text{if} \quad i \notin TrT\,, \\ \left(1 + tax^{GHG}_{grt} EmF^{Y}_{gir}\left(1 - \dfrac{Tr^{\text{Supply}}_{irt}}{Y_{irt}}\right)\right) P^{U}_{rt}\,, & \text{if} \quad i \in TrT\,. \end{cases} \tag{55}$$

In Eq. (54), only the consumption price P^{C}_{ert} has been displayed as an example, but this tax also applies to intermediate consumption price, FOB price, and import demand price when a GHG tariff is implemented. As can be seen, consumption of energy type e is converted into physical quantities through AgC_{ert}, which becomes emission quantities thanks to the emission factor of consumption EmF^{C}_{ger}, which is nothing but the emission per unit of consumption.

The second line is a bit more subtle, as it describes the GHG price intrinsic to the production process, not to the consumption of intermediate inputs; in other words, it is the GHG price of the top-level production functions detailed in Section 2.2. In this regard, the emission factor of production, EmF^{Y}_{gir}, should be understood as a scaling coefficient rather than as emissions per unit of production, since GHG bundles are expressed in terms of emission values and not production quantities. Furthermore, international transportation is not taken into account in the emission cap system.

When free allowances are added, we just reduce the equivalent GHG tax by a quantity tax^{FGHG}_{girt}. This quantity is an exogenous parameter computed for each period of the baseline or simulation, according to the formula:

$$tax^{FGHG}_{girt} = \beta^{FA}_{gir,t-1} tax^{GHG}_{gr,t-1} \frac{\sum_j EmGHG_{gjr,t-1}}{\sum_{j \neq \text{Elec}} EmGHG_{gjr,t-1}}, \tag{56}$$

where β^{FA}_{girt} is the share of free allowances in the market (fixed exogenously).

3 Data

As explained in the introduction, MIRAGE is first calibrated at a reference year, before being incremented year after year in the baseline procedure. In this section, the data used at calibration time are presented. We first mention the main database of the model. Then, trade barrier data—which differ from this main database—are briefly discussed. After that, the elasticities dispersed throughout the model are summarized in a table. Finally, we sketch the most confusing parts of the aggregation and calibration procedures.

3.1 Standard database

Except for data on trade barriers and a bunch of topics detailed in the rest of this section, MIRAGE is calibrated using GTAP 11 standard database. This database features 2017 as the last reference year, which is taken as the calibration year for default applications of the model. It represents the world economy, distinguishing between 65 sectors in 141 countries, accounting for 99.1% of world GDP and 96.4% of world population. GHG emissions are accounted for by the GTAP 11 Satellite Data Base, which distinguishes CO_2 emissions by fuel and by user for each country in the standard database. Non-CO_2 GHG emissions are GTAP 11 estimates, based on data from the Food and Agriculture Organization (FAO) and EDGAR database.

The model cannot run with GTAP fully disaggregated on a personal computer due to computational resource requirements and requires aggregation to approximately 25 regions and 25 sectors.

3.2 Tariff and non-tariff measures

MIRAGE makes use of specific data sets for trade barriers. For tariffs, Market Access Map (MAcMap-HS6) provides a disaggregated, exhaustive, and bilateral measurement of *applied* duties at the product level. It takes regional agreements and trade preferences into account. The raw source data comes from the ITC (UNCTAD-WTO). The HS6 data set is constructed by the CEPII (Guimbard et al. 2012) for analytical purposes and provides *ad valorem* equivalents of applied protection for each triplet importer-exporter-product. The database covers 152 importing and 189 exporting countries.

Ad valorem equivalents of NTM affecting goods are taken from Kee et al. (2009), while those applied to services come from Fontagné, Mitaritonna, et al. (2016).

Trade elasticities are estimations from Fontagné, Guimbard, et al. (2022) for goods. These elasticities, provided at GTAP sectoral level, are estimated using HS6-level information and observing tariff variations across partners, with an underlying structural gravity equation. For services, trade elasticities come from the GTAP database. GTAP-level trade elasticities are aggregated at MIRAGE level to provide sector-level trade elasticities.

3.3 Production function elasticities

Table 1 presents a recap of the various elasticities used throughout the model, with their default values and the source associated with them—the latter being most of the time GTAP or the MIT Emissions Projection and Policy Analysis (EPPA) model (Chen et al. 2022), while CBAM simulation refers to Bellora and Fontagné (2023).

Table 1: Elasticities of substitution for production function

Elasticity	Sectors	Value	Comments
σ^{top}	Standard	0.3	EPPA value
	Energy-intensive	0.11	EPPA value
	Agriculture	0.02	Lowest EPPA value (because EPPA elas include sector substitutions)
	Primary fossil fuel	0.7	Close to EPPA value of 0.6, causing numerical problems
	Petroleum	0	EPPA value
σ^{NFGAS}	Standard	0.11	EPPA value
σ^{NCH4}	Agriculture	0	Leontief structure of MIRAGE
	Energy-intensive	0.15	CBAM simulation value
σ^{NIC}	Agriculture	0.02	Lowest EPPA value (idem σ_{top})
σ^{NN2O}	Energy-intensive	0.2	CBAM simulation value
σ^{NNR}	Fossil	0	EPPA value
σ^{VAQL}	i	σ_i^{VAQL}	GTAP values
σ^{VA}	All	1.1	GTAP value
σ^{Q}	All	0.6	GTAP value
σ^{KE}	All	0.18	Imposed by hand
σ^{E}	All except fossil	0.45	Imposed by hand
	Fossil	0	Leontief structure
σ^{FF}	All except fossil	0.5	Imposed by hand
	Fossil	0	Leontief structure
σ^{NCFF}	All except fossil	0.75	Imposed by hand
	Fossil	0	Leontief structure
σ^{IC}	All	0.6	Imposed by hand
σ^{KG}	All	0.6	Imposed by hand

3.4 Calibration

Once the database has been chosen and aggregated, calibration occurs at the initial year 2017. Share parameters of the production function are straightforward to determine because it is just an inversion of standard CES equations. Thus, only calibration procedures that are rather uncommon are treated in this section.

Before moving on, it should also be noted that the database often comes with some very small values of production for specific countries and sectors. Very small values create numerical problems, so small fluxes are removed from the data when they fall below a given threshold.

3.4.1 Calibration of utility parameters

Utility parameters (minimal consumption level, elasticity of substitution) are calibrated using elasticities from Meade et al. (2014) available from the website of the United States Department of Agriculture (USDA). From this work, we use estimates for 2005 of own-price and income elasticities. Because the LES-CES can only accommodate positive income elasticities, we change all negative income elasticities to a very low value, namely 0.025.

All the parameters are calibrated simultaneously using an optimization procedure that minimizes the discrepancies between target and calibrated own-price elasticities, subject to the adherence to initial consumption and income elasticities. The calibration is done on the consumption per capita.

For each country, the calibration follows the program

$$\min_{\sigma_r^C,\, 0\leq \bar{c}_{ir}\leq C_{ir0},\, \alpha_{ir}^C} \sum_i \frac{P_{ir0}^C C_{ir0}^t}{BudC_{r0}} \left(e_{ir} - e_{ir}^t\right)^2, \tag{57}$$

subject to

$$C_{ir0} = \bar{c}_{ir} + \frac{\alpha_{ir}^C \left(BudC_{r0} - \gamma_r\right)}{P_{r0}^U} \left(\frac{P_{r0}^U}{P_{ir0}^C}\right)^{\sigma_r^C}, \tag{58}$$

$$e_{ir} = -\frac{\alpha_{ir}^C \sigma_r^C}{C_{ir0}} \left(\frac{P_{r0}^U}{P_{ir0}^C}\right)^{\sigma_r^C - 1} \left(\bar{c}_{ir} - C_{ir0} + \frac{BudC_{r0} - \gamma_r}{P_{ir0}^C}\right), \tag{59}$$

$$\eta_{ir} = \frac{\alpha_{ir}^C BudC_{r0}}{P_{ir0}^C C_{ir0}} \left(\frac{P_{r0}^U}{P_{ir0}^C}\right)^{\sigma_r^C - 1}, \tag{60}$$

where e_{ir}^t is the target own-price elasticity, C_{ir0} is the target consumption level (from the GTAP database), $\gamma_r = \sum_i P_{ir0}^C \bar{c}_{ir}$ is the total value of incompressible consumption, $P_{r0}^U = [\sum_i \alpha_i (P_{ir0}^C)^{1-\sigma_r^C}]^{1/(1-\sigma_r^C)}$ is the price index of utility, and η_{ir} is the income elasticity.

3.4.2 Calibration of imperfect competition

Generalized marginal cost $GnMC_{irt}$ is a function of the number of firms N_{irt} and the elasticity of substitution between varieties σ_{VAR}. Although N_{irt} is a variable that varies over time, it theoretically depends on fixed costs, which are parameters to be calibrated. In this framework, the markup is constant and does not depend on the number of firms, so we can normalize $N_{ir,0} = 100$ at calibration time without losing generality. For the elasticity of substitution between varieties, we stick to MIRAGE's traditional rule of $\sqrt{2}$ for elasticities of substitution:

$$\sigma_{\text{VAR}} - 1 = \sqrt{2}\left(\sigma_{\text{IMP}} - 1\right) .$$

Fixed costs are then derived through the zero-profit condition (see Eq. (33)):

$$fc_{ir} = N_{ir,0}^{\frac{1}{1-\sigma_{\text{VAR}}}} \frac{Y_{ir,0}}{\sigma_{\text{VAR}} - 1} . \tag{61}$$

Then, by reverting this equation valid for all time, N_{irt} is fully determined—and by extension, the generalized marginal cost.

3.4.3 Calibration of investment allocation

Investment allocation is a function of multiple variables, including capital stock, rate of return, and price of total investment, as detailed in Eq. (41). Two parameters also play a role: the depreciation rate of capital δ_r, and an elasticity α representing the speed at which investment reallocates.

The depreciation rate is set at 6%, in agreement with the average value of capital depreciation measured empirically. For the value of α, we use the same argument as in previous versions of the model:

> "Since α cannot be calibrated, two static models were built, corresponding to a short run and a long run version of Mirage. We applied the same shocks to both of them and chose α so that half the adjustment of capital stocks towards the long run would be made in around 4 years, for a variety of small commercial shocks. It gave the value $\alpha = 40$." (Bchir et al. (2002))

4 Baseline

MIRAGE baseline implements MAGE model macroeconomic projections. It draws the following variables from MAGE output, the EconMap database:

- GDP projections,

- Population,
- Skilled and unskilled labor,
- Saving rates and current account balances,
- Energy productivity.

In addition to these variables from EconMap, other assumptions are included in the baseline:

- Fossil energy price trajectories are calibrated according to International Energy Agency (IEA) projections.
- Sector decomposition of TFP growth among agriculture, manufacturing, and services is also imposed.

By default, the baseline exercise is composed of two steps of model simulation (see Fig. 9 for a graphical representation):

1. Projection in macroeconomic determinants. It is also possible to include other assumptions in this step, provided they are not likely to have a significant impact on GDP growth. It is the standard "baseline" that is common to most CGE models. In this step, the GDP trajectory is imposed on the model in order to calibrate the trajectory of TFP growth.
2. Other assumptions are implemented in the second step (for instance, Brexit, the Paris Agreement, large free trade agreements, etc.). This step takes productivity as calibrated in Step 1, and lets GDP be endogenous. This allows for accounting for the effect of baseline assumptions on GDP and energy prices.

After that, the scenario of the desired simulation can be implemented and compared to these reference steps. Like in the second step, GDP is endogenous since TFP is taken as given by the baseline; it allows simulating the effect of a policy on this variable. In the rest of this section, we present a broad picture of the MaGE model, together with the other variables that are fixed in the baseline process.

4.1 Macroeconomic projections

In order to implement our baseline exercise, we use the long-run growth projections from MaGE model (Fontagné, Perego, et al. 2022; Fouré et al. 2013). These projections are based on a three-factor (capital, labor, energy) production function at national level, for 167 countries. First, we briefly describe the methodology underlying such projections.

These three factors are gathered in a CES function of energy E_{rt} and a Cobb-Douglas aggregate of capital K_{rt} and labor L_{rt}:

$$Y_{rt} = \left[\left(A_{rt} K_{rt}^{\alpha} L_{rt}^{1-\alpha}\right)^{\frac{\sigma-1}{\sigma}} + \left(B_{rt} E_{rt}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{62}$$

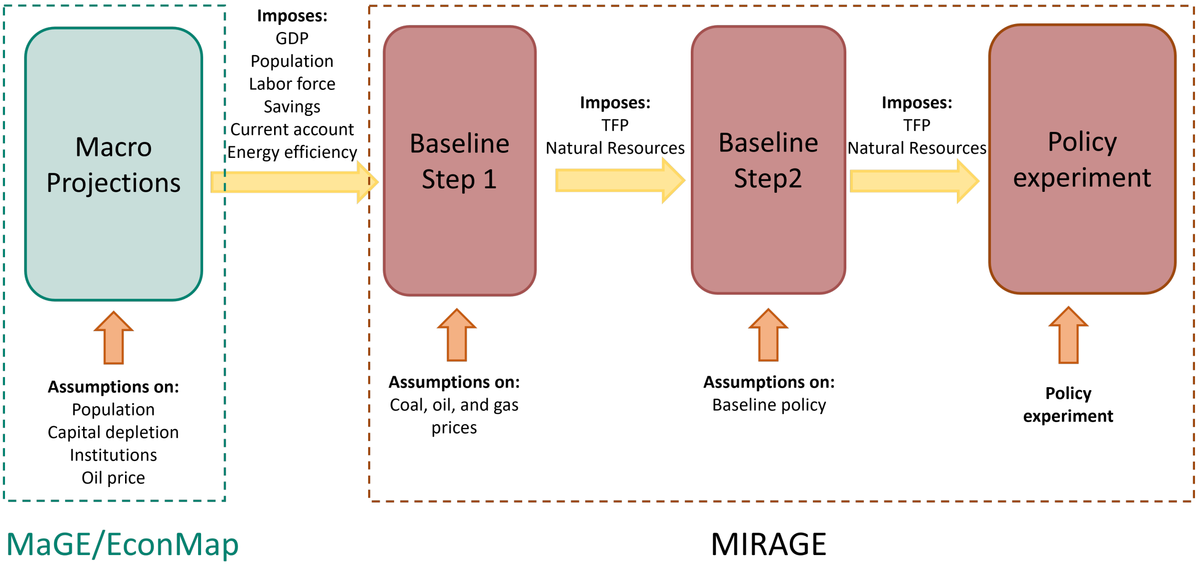


Figure 9: The simulation workflow with 2-step baseline

where A_{rt} and B_{rt} are respectively the usual TFP—in our case the efficiency of labor and capital combined—and an energy-specific productivity. In line with the literature (see, for example, Mankiw et al. 1992), α is set to 0.3. In turn, the $\sigma = 0.2$ parameter is calibrated, within the range estimated by van der Werf (2008) but also considering that services are not included in these estimations, and the shape of energy productivity must not be reduced to an inverse function of energy price (Fouré et al. 2013). Moreover, GDP $Y_{r,t}$, where appropriate, is considered net of oil rents to avoid a biased measure of productivity. Oil rents are added separately and are assumed to be pure rents: the volume of production is constant, but its real value (in terms of the GDP deflator) increases with the relative price of oil.

This model is fitted with UN population projections as well as econometric estimations for capital accumulation, education, female participation in the labor force, and two types of technical progress. Savings are based on the demography: it is the deformation of the population pyramids that gives the evolution of the regional saving rates. The energy consumption factor is not directly projected; it is recovered from firms' optimization programs.

In particular, capital accumulation follows a permanent inventory process, where the stock of capital increases each year with investment but can also be depleted. The depletion rate is set in accordance with the MIRAGE model at 6%, whereas investment-to-GDP ratios depend on saving rates through an error-correction Feldstein–Horioka-type relationship. This allows relaxation of the common assumption of a closed economy. Savings rates are determined by both demographic and economic situations, in line with life-cycle theory.

The two productivity measures follow catch-up processes. While TFP growth is fueled by education levels, energy productivity growth is tempered by the levels of GDP per capita, such that it mimics the impact of sectoral changes on energy productivity during a country's development process.

4.2 Total factor productivity

Total factor productivity in MIRAGE consists of a region-specific TFP, TFP_{rt}, and a sector-specific component, $TFPJ_{jrt}$. Both concern only energy and the five factors (capital, skilled labor, unskilled labor—embodied in the $VAQL_{j,r,t}$ bundle—as well as land and natural resources) of the production function:

$$VAQL_{jrt} = a_{jr}^{VAQL} VA_{jrt} \left(TFP_{rt} TFPJ_{j,r,t}\right)^{\sigma^{VAQL}-1} \left(\frac{P_{jrt}^{VA}}{P_{jrt}^{VAQL}}\right)^{\sigma^{VAQL}}, \quad (63)$$

$$Land_{jrt} = a_{jr}^{Land} VA_{jrt} \left(TFP_{rt} TFPJ_{jrt}\right)^{\sigma^{VAQL}-1} \left(\frac{P_{jrt}^{VA}}{P_{jrt}^{Land}}\right)^{\sigma^{VAQL}}, \quad (64)$$

$$NatRes_{jrt} ResV_{jt} = a_{jr}^{NatRes} VA_{jrt} \left(TFP_{rt} TFPJ_{jrt}\right)^{\sigma^{VAQL}-1} \left(\frac{P_{jrt}^{VA}}{P_{jrt}^{NatRes}}\right)^{\sigma^{VAQL}}. \quad (65)$$

Calibration in the baseline exercise

MIRAGE baseline (in Step 1) exercise starts from the following assumptions in order to calibrate a baseline trajectory for TFP:

- MaGE GDP growth rates, g_{rt}^{GDP}
- Exogenous agricultural TFP, $TFPi_{irt}$
- Constant 2 p.p. growth difference between manufacturing and services, ϕ_{irt}^{p}

This translates in the following relations (star denotes variables measured at initial prices):

$$GDP_{rt}^{*} = \left(1 + g_{rt}^{GDP}\right) GDP_{r,t-1}^{*}, \quad (66)$$

$$TFPJ_{irt} TFP_{rt} = \begin{cases} TFPi_{irt} & \text{if } i \in \text{Agri}, \\ \left(1 + \phi_{irt}^{p}\right) TFPJ_{ir,t-1} TFP_{rt} & \text{if } i \notin \text{Agri}. \end{cases} \quad (67)$$

4.3 Population, labor, and current account

Population and labor by educational level are simply following the growth rate from EconMap:

$$Pop_{rt} = ActivePopulation_{rt} \,, \tag{68}$$
$$UnSkL^{\text{TOT}}_{rt} = UnSkL^{\text{TOT}}_{r,t-1}\left(1 + g^{UnSkL}_{rt}\right) \,, \tag{69}$$
$$SkL^{\text{TOT}}_{rt} = SkL^{\text{TOT}}_{r,t-1}\left(1 + g^{SkL}_{rt}\right) \,. \tag{70}$$

Current account balances CA_{st} are used in the macroeconomic closure equation Eq. (48). Saving rates follow EconMap projections $Savings_{rt}$ additively,

$$Sav_{rt} = Sav_{r,t-1} + \left(Savings_{r,t} - Savings_{r,t-1}\right) \,, \tag{71}$$

while current account balances evolve additively,

$$CA_{rt} = CA_{r,t-1} + \Delta CA_{rt} \,. \tag{72}$$

ΔCA_{rt} is calibrated after EconMap's $CurrentAccount_{rt}$, but keeping world current account balanced:

$$\begin{aligned} \Delta CA^0_{rt} &= CurrentAccount_{rt}\frac{GDP^*rt}{\sum_s GDP^*st} - CurrentAccount_{r,t-1}\frac{GDP^*r,t-1}{\sum_s GDP^*s,t-1} \,, \\ \Delta CA_{rt} &= \Delta CA^0_{rt} - \left(\sum_s \Delta CA^0_{st}\right)\frac{GDP^*rt}{\sum_s GDP^*st} \,. \end{aligned} \tag{73}$$

4.4 Energy and GHG emissions

4.4.1 Energy productivity

In MIRAGE, total energy consumption by each sector E^{TOT}_{jrt} is subject to energy-specific technological improvement EE_{jrt}:

$$E^{\text{TOT}}_{jrt} = a^E_{jrt} EE_{jrt} KE_{jrt}\left(\frac{PKE_{jrt}}{PE_{jrt}}\right)^{\sigma^{KE}} \,. \tag{74}$$

EE_{jrt} is applied to every sector, except for non-electricity energy producing sectors (coal, oil, gas, petroleum and coal products), whose energy productivity is constant.

Baseline calibration

This energy-specific technological improvement is calibrated in the baseline after MaGE's projected energy productivity B_{rt}. However, three things differ between B_{rt} and EE_{jrt}:

- In MIRAGE notations, share coefficients and productivity improvement appear in CES functions at the power of $1/\sigma$ whereas in MaGE, B_{rt} appears at the power of $(\sigma - 1)/\sigma$. We therefore introduce $EProd_{r,t}$:

$$EProd_{rt} \equiv B_{rt}^{\sigma^{KE}-1}.$$

- B_{rt} is labelled in dollars per ton of oil equivalent, whereas EE_{jrt} and $EProd_{r,t}$ are calibrated at 1:

$$EProd_{jrt} = EProd_{jr,t-1}\left(1 + g_{rt}^{B}\right)^{\sigma^{KE}-1}.$$

- In MaGE's production function, B_{rt} (as well as capital-labor productivity A_{rt}) includes a hypothetical TFP, whereas in MIRAGE, EE_{jrt} comes in addition to the TFP level $TFP_{rt}TFPJ_{jrt}$:

$$EE_{jrt} = \left(\frac{EProd_{rt}}{TFP_{rt}TFPJ_{jrt}}\right)^{\sigma^{KE}-1}.$$

4.4.2 GHG emissions

In order to compute, at each period, the shadow price of GHG emissions, MIRAGE needs the Nationally Determined Contributions (NDC) to the Paris Agreement of each country. These NDC are split into three different types:

- Absolute target: the reduction in carbon emissions is computed in absolute value compared to a reference year (most often 1990). This is for instance the case of the EU.
- Intensity target: the carbon emission cap is expressed as a percentage of GDP. This is for instance the case of China.
- Business as usual (BAU): the reduction in carbon emissions is computed compared to a baseline where no carbon policy is implemented.

The data on these NDC is collected from the registry of the United Nations Climate Change.

4.5 Natural resources

Fossil fuel energy prices

Fossil fuel energy prices are exogenous in the baseline, fixed according to IEA projections in year 2021. Figure 10 displays a graphical representation of these trajectories, with the understanding that baseline calibration makes use of the medium scenario.

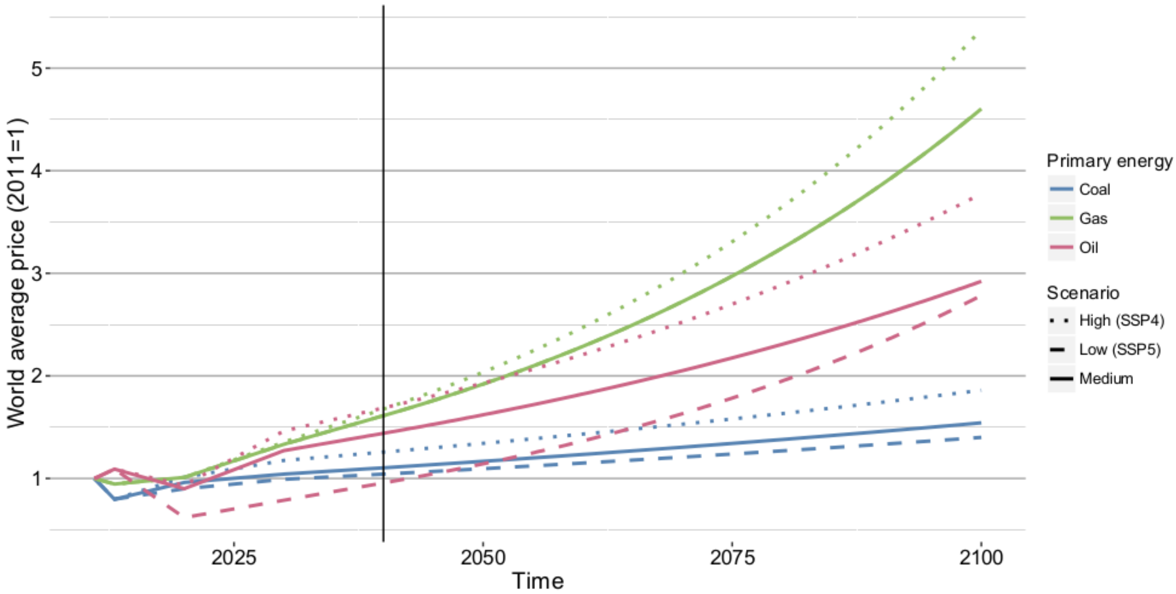


Figure 10: Energy price projections from World Energy Outlook 2015

Natural resources

In Mirage, a sector-specific reserve factor $ResV_{jt}$ is introduced to scale natural resources globally for each primary fossil energy (coal, oil, gas):

$$NatRes_{irt} ResV_{it} = a_{ir}^{NatRes} Y_{irt} \left(\frac{P_{rt}^{Y}}{P_{rt}^{NatRes}} \right)^{\sigma^{NatRes}} . \tag{75}$$

Calibration of natural resources in the baseline

During the baseline exercise, the reserve factor is set endogenously, while world price defined as

$$\log \left(P_{it}^{W} PO_{i}^{W} \right) = \frac{\sum_{r,s} Trade_{irst} \log P_{irst}^{\text{CIF}}}{\sum_{r,s} Trade_{irst}} , \tag{76}$$

is kept exogenous:

$$P_{it}^{W} = P_{i,t-1}^{W} \left(1 + g_{it}^{P} \right) . \tag{77}$$

Appendix

A List of sets, parameters, and variables

A.1 Notations

In general, superscripts for prices P refer to the related variables, while superscripts for share parameters a refer to the related calibrated coefficient in a CES function. The same convention applies for elasticities σ: the superscript indicates the output variable of the CES nest (e.g., σ_i^{KE} is the elasticity of substitution between capital and energy, in the bundle KE). X^* denotes variable X measured at initial prices.

The following convention is used for sets:

i, j: Sectors. i is used preferentially for goods while j represents sectors.

r, s: Regions.

t: Time period.

A.2 Parameters definition

Table 2: List of MIRAGE's parameters

Doc notation	MIRAGE notation	Description
Demand		
$\bar{c}_{ir}$	`cmin(i,r)`	Minimal consumption of good i in the final demand of region r
Pop_{rt}	`Pop_ag("Totpop",r,t)`	Population in region r
e_{ii}^t	`EPr(i,r)`	Target uncompensated own-price elasticity
η_i^t	`EInc(i,r)`	Target income elasticity
σ_i^{ARM}	`sigma_ARM(i)`	Armington elasticity of substitution btw domestic and foreign goods
σ_i^{IMP}	`sigma_IMP(i)`	Elasticity of substitution btw imported goods
Supply and factors		
Gel_{jrt}	`Gel(i,r,t,sim)`	Land use rate
$b_{Ltype,r}^{Lt}$	`b_Lt(Ltype,r,sim)`	Dual labor CET calibration parameter

b^{TE}_{ir}	`b_TE(i,r)`	Land CET calibration parameter
EE_{irt}	`EProd(i,r,t,sim)`	Energy productivity

Transportation

μ_{irs}	`mu(i,r,s)`	Demand of transport per unit of traded volume between r and s
a^{Tr}_{jirs}	`a_Tr(j,i,r,s)`	Share of each transport mode j in trade flows i
c^{Tr}_{i}	`c_T(i)`	Cobb–Douglas scale coefficient for transportation

Imperfect competition

fc_{ir}	`fc(i,r)`	Fixed cost for one unit of output
$\sigma^{\mathrm{VAR}}_{i}$	`sigma_VAR(i)`	Variety elasticity of substitution

Taxes and equivalent

tax^{P}_{irt}	`taxP(i,r,t,sim)`	Production tax rate
tax^{C}_{irt}	`taxC(i,r,t,sim)`	Consumption tax rate
tax^{KG}_{irt}	`taxKG(i,r,t,sim)`	Capital goods tax rate
tax^{IC}_{ijrt}	`taxIC(i,j,r,t,sim)`	Intermediate consumption tax rate
tax^{EIC}_{ijrt}	`taxIC(i,j,r,t,sim)`	Energy intermediate consumption tax rate
$tax^{\mathrm{EXP}}_{irst}$	`taxEXP(i,r,s,t,sim)`	Export tax rate from r to s
$tax^{\mathrm{MFA}}_{irst}$	`taxMFA(i,r,s,t,sim)`	Export tax equivalent to MFA quotas
$Tariff_{irst}$	`Tariff(i,r,s,t,sim)`	Tariff rate from r to s
sub^{Land}_{irt}	`subf("Land",i,r,t,sim)`	Land subsidies
sub^{UnSkL}_{irt}	`subf("UnSkLab",i,r,t,sim)`	Unskilled labor subsidies
sub^{SkL}_{irt}	`subf("SkLab",i,r,t,sim)`	Skilled labor subsidies
$sub^{Capital}_{irt}$	`subf("Capital",i,r,t,sim)`	Capital subsidies
$rente_{irst}$	`rente(i,r,s,t,sim)`	Tariff rate quotas rent
$tCost_{irst}$	`tCostTF(i,r,s,t,sim)`	Iceberg trade cost
$tax^{\mathrm{SER}}_{irst}$	`taxSER(i,r,s,t,sim)`	*Ad valorem* equivalent for protection in services
NTM_{irst}	`NTM(i,r,s,t,sim)`	*Ad valorem* equivalent for NTM
$shareNTM^{tCost}_{irs}$	`shareNTM_tCost(i,r,s)`	Allocation of NTM to iceberg trade cost
$shareNTM^{Tariff}_{irs}$	`shareNTM_Tariff(i,r,s)`	Allocation of NTM to tariff
$shareNTM^{tax^{\mathrm{EXP}}}_{irs}$	`shareNTM_taxEXP(i,r,s)`	Allocation of NTM to export tax

Capital and macroeconomics

Sav_{rt}	`Sav(r,t)`	Saving rate
B_{rt}	`B(r,t,sim)`	Scale coefficient for investment by region r
a_{irs}	`a(i,r,s)`	Investment scale coefficient
α	`alpha`	Elasticity of investment to return on capital
δ_r	`delta(r)`	Capital depreciation rate
ϕ^p_{irt}	`phi_p(i,r,t,sim)`	Exogenous shifter btw manufacturing and services productivity growth
g^{GDP}_{rt}	`GROWTH(r,t,sim)`	Exogenous baseline growth
$TFPi_{irt}$	`TFPi(i,r,t)`	Sectoral TFP for agricultural sectors

Energy and emissions

$GHGCap_{grt}$	`GHGCap(c_em,t,sim)`	Exogenous cap on GHG emissions
$GHGTax_{grt}$	`GHGtax(c_em,t,sim)`	Exogenous tax on GHG emissions
ϵ^{IC}_{ejr}	`EVoleFactIC(e,j,r)`	Conversion coefficient for energy content of intermediate consumption
ϵ^{C}_{er}	`EVoleFactH(e,j,r)`	Conversion coefficient for energy content of final consumption
ϵ^{Y}_{er}	`EVoleFactY(e,j,r)`	Conversion coefficient for energy content of production
ϵ^{D}_{er}	`EVoleFactD(e,j,r)`	Conversion coefficient for energy content of final demand
ϵ^{Dem}_{ers}	`EVoleFactDEM(e,j,r)`	Conversion coefficient for energy content of trade
β^{FA}_{girt}	`share_FreeAllow(c_em,t,sim)`	Share of free allowances in carbon market
EmF^{Y}_{gir}	`EmFactorGHG_Y(ghgs,i,r)`	Emission factor of production process i
EmF^{C}_{ger}	`EmFactorGHG_C(ghgs,e,r)`	Emission factor of energy type e final consumption
EmF^{IC}_{geir}	`EmFactorGHG_IC(ghgs,e,i,r)`	Emission factor of energy type e intermediate consumption by sector i

A.3 Variable definition

Table 3: List of Mirage's variables

Documentation notation	Mirage notation	Description
Demand		
$BudC_{rt}$	`BUDC(r,t,sim)`	Budget devoted to final consumption
U_{rt}	`U(r,t,sim)`	Utility
C_{irt}	`C(i,r,t,sim)`	Final consumption
IC_{ijrt}	`IC(i,j,r,t,sim)`	Intermediate consumption of good i by sector j
Inv_{rt}^{TOT}	`INVTOT(r,t,sim)`	Total investment in region r
KG_{irt}	`KG(i,r,t,sim)`	Capital good demand by sector i
Dem_{irt}^{TOT}	`DEMTOT(i,r,t,sim)`	Total demand of good i
D_{ist}	`D(i,s,t,sim)`	Demand of domestic goods
M_{ist}	`M(i,s,t,sim)`	Import demand by s
Dem_{irst}	`DEM(i,r,s,t,sim)`	Import demand from r to s
Supply		
Y_{irt}	`Y(i,r,t,sim)`	Output of sector i
VA_{irt}	`VA(i,r,t,sim)`	Value added
$CNTER_{irt}$	`CNTER(i,r,t,sim)`	Aggregate intermediate consumption
$VAQL_{irt}$	`VAQL(i,r,t,sim)`	Value added from Q and L
NNR_{irt}	`NNR(i,r,t,sim)`	Non-natural resources
Q_{irt}	`Q(i,r,t,sim)`	KE-skilled labor bundle
KE_{irt}	`KE(i,r,t,sim)`	Capital and energy bundle
TFP_{rt}	`TFP(r,t,sim)`	Total factor productivity
$TFPJ_{irt}$	`TFPJ(i,r,t,sim)`	Sectoral factor productivity
Factors		
$NatRes_{irt}$	`NatRes(i,r,t,sim)`	Natural resources
$ResV_{it}$	`RESV(i,t,sim)`	Reserve coefficient
$Land_{irt}$	`Land(i,r,t,sim)`	Land
$UnSkL_{irt}$	`UnSkL(i,r,t,sim)`	Unskilled labor
SkL_{irt}	`SkL(i,r,t,sim)`	Skilled labor
$Capital_{irt}$	`Capital(i,r,t,sim)`	Capital stock of firms in sector i

Energy supply

$Energy_{irt}$	`Energy(i,r,t,sim)`	Energy bundle
$Electricity_{irt}$	`Electricity(i,r,t,sim)`	Aggregate electricity consumed by sector i
$Power_{rt}$	`ElEY(r,t,sim)`	Aggregate electricity produced in r
$ElTD_{rt}$	`ElTD(r,t,sim)`	Electricity transmission and distribution activities
$ElGe_{rt}$	`ElGE(r,t,sim)`	Electricity generation activities
ElB_{rt}	`ElB(r,t,sim)`	Base load electricity demand
ElP_{rt}	`ElP(r,t,sim)`	Peak load electricity demand
$ElBase_{jrt}$	`ElBaseD(j,r,t,sim)`	Pure base load electricity (by default, j runs over nuclear, coal and base hydro electricity)
$ElPeak_{jrt}$	`ElPeakD(j,r,t,sim)`	Pure peak load electricity (by default, j runs over gas, oil and peak hydro electricity)
$ElIntB_{jrt}$	`ElIntB(j,r,t,sim)`	Intermittent electricity distributed to base load (by default, j runs over wind and solar electricity)
$ElIntP_{jrt}$	`ElIntP(j,r,t,sim)`	Intermittent electricity distributed to peak load (by default, j runs over wind and solar electricity)
$Coal_{irt}$	`Coal(i,r,t,sim)`	Coal
Oil_{irt}	`Oil(i,r,t,sim)`	Oil
Gas_{irt}	`Gas(i,r,t,sim)`	Gas
$Petroleum_{irt}$	`Petroleum(i,r,t,sim)`	Refined petroleum
$FFuel_{irt}$	`FFuel(i,r,t,sim)`	Fossil fuels (coal, gas, oil, refined oil)
$NCFFuel_{irt}$	`NCFFuel(i,r,t,sim)`	Non-coal fossil fuels
EIC_{ijrt}	`EIC(i,j,r,t,sim)`	Intermediate consumption of energy good i used in sector j

Factor market

SkL_{rt}^{TOT}	`TotalSkL(r,t,sim)`	Total skilled labor
$UnSkL_{rt}^{TOT}$	`TotalUnSkL(r,t,sim)`	Total unskilled labor
$Land_{rt}^{TOT}$	`TotalLand(r,t,sim)`	Total land
$Capital_{rt}^{TOT}$	`TotalCapital(r,t,sim)`	Total capital
$Lt_{Ltype,rt}$	`Lt(Ltype,r,t,sim)`	Unskilled labor supply of type *Ltype*
W_{irt}^{X}	`WX(i,r,t,sim)`	Return rate of factor X in sector i

$W_{rt}^{X\text{TOT}}$	`WTotalX(r,t,sim)`	Shadow price of factor X

Good market

$Trade_{irst}$	`TRADE(i,r,s,t,sim)`	Bilateral trade in volume (from r to s)
$YtoVol_{irt}$	`YtoVol(i,r,t,sim)`	Conversion coefficient btw Y and production volume
P_{irst}^{FOB}	`PFOB(i,r,s,t,sim)`	FOB price
P_{irst}^{CIF}	`PCIF(i,r,s,t,sim)`	CIF price
$GnTax_{irst}^{\text{EXP}}$	`GnTaxEXP(i,r,s,t,sim)`	Generalized export tax
$GnTrf_{irst}$	`GnTariff(i,r,s,t,sim)`	Generalized tariff
$GnTC_{irt}$	`GnTC(i,r,t,sim)`	Generalized trade cost

Transportation

Tr_{irst}	`Tr(i,r,s,t,sim)`	Transport demand by export from r to s
$\tilde{T}r_{jirst}$	`TrMode(j,i,r,s,t,sim)`	Transport demand per mode j for sector i
Tr_{jrt}^{Supply}	`TrSupply(j,r,t,sim)`	Transport mode supply
$World_{jt}^{Tr}$	`WorldTr(j,t,sim)`	World supply of international transport

Imperfect competition

$GnMC_{irt}$	`GnMC(i,r,t,sim)`	Generalized marginal cost
N_{irt}	`NB(i,r,t,sim)`	Number of firms

Income and tax revenues

$RevTax_{irt}^{P}$	`ProdTaxREV(i,r,t,sim)`	Production tax revenue
$Revtax_{irt}^{\text{EXP}}$	`ExpTaxREV(i,r,t,sim)`	Export tax revenue
$RevTariff_{irt}$	`TariffREV(i,r,t,sim)`	Tariff revenue
$RevNTM_{rt}$	`NTMRentsREV(r,t,sim)`	NTM rents revenue
$RevTax_{irt}^{C}$	`ConsTaxREV(i,r,t,sim)`	Consumption tax revenue
$RevTax_{rt}^{GHG}$	`GHGTaxREV(r,t,sim)`	GHG tax revenue
$RevTax_{rt}$	`TaxREV(r,t,sim)`	Total tax revenue
Rev_{rt}	`REV(r,t,sim)`	Total revenue
$WGDP_{t}$	`WGDPVAL(t,sim)`	World GDP value
GDP_{rt}	`GDP(r,t,sim)`	GDP value

Capital and macroeconomics

CA_{rt}	`CABal(r,t,sim)`	Current account surplus (without FDIs)

Inv_{irst}	`INV(i,r,s,t,sim)`	Investment by r in s
K_{irst}	`K(i,r,s,t,sim)`	Capital stock invested by r in s
$DemNA_{irt}$	`VDEMTOT(i,r,t,sim)`	Value of total demand under national accounting method
CNA_{irt}	`CNA(i,r,t,sim)`	Consumption under national accounting method
$KGNA_{irt}$	`KGNA(i,r,t,sim)`	Capital goods under national accounting method

Energy and GHG emissions

GHG_{girt}	`GHG(ghgs,i,r,t,sim)`	GHG emission of gas g coming from the production process of i
GHG^{IC}_{geirt}	`GHG_IC(ghgs,i,j,r,t,sim)`	GHG emissions from energy type e consumed in process i
AgC_{irt}	`AgCons(i,r,t,sim)`	Consumption aggregation coefficient
$AgDem_{irt}$	`AgDem(i,r,t,sim)`	Demand aggregation coefficient
$EmGHG^{Y}_{girt}$	`EmGHG_Y(ghgs,i,r,t,sim)`	GHG emissions from output
$EmGHG^{H}_{gert}$	`EmGHG_C(ghgs,i,r,t,sim)`	GHG emissions from households
$EmGHG^{IC}_{gejrt}$	`EmGHG_IC(ghgs,i,j,r,t,sim)`	GHG emissions from intermediate consumption
$EmGHG_{grt}$	`EmGHG(ghgs,r,t,sim)`	GHG emissions by region
$EmGHG^{Dem}_{girst}$	`EmGHGDEM(ghgs,i,r,s,t,sim)`	GHG content of traded good
tax^{GHG}_{grt}	`taxGHG(c_em,t,sim)`	Equivalent carbon tax from carbon markets
tax^{FGHG}_{girt}	`taxGHG_FreeAllow(c_em,i...)`	Equivalent reduction in carbon tax from free allowances
E^{IC}_{ejrt}	`EVoleIC(i,j,r,t,sim)`	Gross energy consumption (Mtoe) by firms' intermediate consumption
E^{C}_{ert}	`EVoleC(i,r,t,sim)`	Gross energy consumption (Mtoe) by households
E^{Y}_{ert}	`EVoleY(i,r,t,sim)`	Energy production (Mtoe)
E^{D}_{ert}	`EVoleD(i,r,t,sim)`	Local demand for local energy (Mtoe)
E^{Dem}_{erst}	`EVoleDEM(i,r,s,t,sim)`	Energy volume bilateral trade (Mtoe)
E^{DemTOT}_{ert}	`EVoleDEMTOT(i,r,t,sim)`	Total demand of energy by r
EC_{ert}	`EVoleCons(i,r,t,sim)`	Energy consumption (Mtoe)

B List of equations

In this section are provided all the equations implemented in the model, in the most explicit way. Variables and parameters can be found in Section A; thus, they are not redefined here.

B.1 Demand

The representative household maximizes LES-CES utility under the budget constraint,

$$\begin{aligned} \max U_{rt} &= \left[\sum_i a^C_{ir}\left(\frac{C_{irt}}{Pop_{rt}} - \bar{c}_{ir}\right)^{(\sigma^C_r-1)/\sigma^C_r}\right]^{\sigma^C_r/(\sigma^C_r-1)}, \\ \text{s.t.}\quad BudC_{rt} &= \sum_i P^C_{irt} C_{irt}\,. \end{aligned} \tag{B.1}$$

By solving this program, the optimal consumption is given as,

$$\begin{aligned} C_{irt} &= Pop_{rt}\left[\bar{c}_{ir} + a^C_{ir} U_{rt}\left(\frac{P^U_{rt}}{P^C_{irt}}\right)^{\sigma^C_r}\right], \\ P^U_{rt} U_{rt} &= \sum_i P^C_{irt}\left(\frac{C_{irt}}{Pop_{rt}} - \bar{c}_{ir}\right). \end{aligned} \tag{B.2}$$

Consumption price P^C_{irt} is the price of total demand with consumption tax. For commodities which do not concern households' CO_2 emissions

$$P^C_{irt} = P^{DemTOT}_{irt}(1 + tax^C_{irt})\,. \tag{B.3}$$

For commodities which concern household CO_2 emissions (energy consumption), a carbon tax will be added to consumption price,

$$P^C_{ert} = P^{DemTOT}_{ert}(1 + tax^C_{ert}) + \sum_g tax^{GHG}_{grt} AgC_{ert} EmF^C_{ger} P^U_{rt}\,. \tag{B.4}$$

B.2 Supply

Supply side is composed of nested CES functions. Instead of writing down each equation, it is more practical to look at a single nest structure. In this general example, we denote by Y the output and X_k the inputs, indexed by k running over an arbitrary number. To be in line with the conventions used so far, the share parameter associated with input X_k is denoted a^X_k.

General case

In the general case with an elasticity of substitution $\sigma^Y > 0$, the maximization program is

$$\begin{cases} \max \Pi = P^Y Y - \sum_k P_k^X X_k \,, \\ \text{s.t.} \quad Y = \left(\sum_k a_k^X X_k^{\frac{\sigma^Y - 1}{\sigma^Y}} \right)^{\frac{\sigma^Y}{\sigma^Y - 1}} \,. \end{cases} \tag{B.5}$$

Therefore, the following equations must hold at equilibrium:

$$\begin{aligned} P^Y Y &= \sum_k P_k^X X_k \,, \\ \forall k, \quad X_k &= Y \left(\frac{a_k^X P^Y}{P_k^X} \right)^{\sigma^Y} \,. \end{aligned} \tag{B.6}$$

Leontief case

If $\sigma^Y = 0$, the maximization program becomes

$$\begin{cases} \max \Pi = P^Y Y - \sum_k P_k^X X_k \,, \\ \text{s.t.} \quad Y = \min \left\{ \frac{X_k}{a_k^X} \right\} \,, \end{cases} \tag{B.7}$$

so that

$$\begin{aligned} P^Y Y &= \sum_k P_k^X X_k \,, \\ \forall k, \quad X_k &= a_k^X Y \,. \end{aligned} \tag{B.8}$$

B.3 Power supply

Power supply is no more difficult than the CES equations presented above. However, because electricity activities are regrouped under variable names that might be unclear, we provide a full list of the equations.

Electricity generation is a Leontief between base and peak load:

$$P_{rt}^{ElGe} ElGe_{rt} = P_{rt}^{ElB} ElB_{rt} + P_{rt}^{ElP} ElP_{rt} \,, \tag{B.9}$$

$$ElB_{rt} = a_r^{ElB} ElGe_{rt} \,, \tag{B.10}$$

$$ElP_{rt} = a_r^{ElP} ElGe_{rt} \,. \tag{B.11}$$

Base load electricity is composed of pure base load electricity activities (whose sectors are indexed by $i_b \in EL\_BL$) and intermittent electricity activities (whose sectors are indexed by $i_i \in EL\_INT$):

$$\begin{aligned}
P^{ElB}_{rt} ElB_{rt} &= \sum_{i_b} P^{ElBase}_{i_b rt} ElBase_{i_b rt} + \sum_{i_i} P^{ElIntB}_{i_i rt} ElIntB_{i_i rt}\,, \\
ElBase_{i_b rt} &= ElB_{rt} \left(\frac{a^{ElBase}_{i_b r} P^{ElBase}_{i_b rt}}{P^{ElB}_{rt}} \right)^{\sigma^{ElB}}, \\
ElIntB_{i_i rt} &= ElB_{rt} \left(\frac{a^{ElIntB}_{i_i r} P^{ElIntB}_{i_i rt}}{P^{ElB}_{rt}} \right)^{\sigma^{ElB}}.
\end{aligned} \tag{B.12}$$

Likewise, for peak load electricity

$$\begin{aligned}
P^{ElP}_{rt} ElP_{rt} &= \sum_{i_p} P^{ElPeak}_{i_p rt} ElPeak_{i_p rt} + \sum_{i_i} P^{ElIntP}_{i_i rt} ElIntP_{i_i rt}\,, \\
ElPeak_{i_p rt} &= ElP_{rt} \left(\frac{a^{ElPeak}_{i_p r} P^{ElPeak}_{i_p rt}}{P^{ElP}_{rt}} \right)^{\sigma^{ElP}}, \\
ElIntP_{i_i rt} &= ElP_{rt} \left(\frac{a^{ElIntP}_{i_i r} P^{ElIntP}_{i_i rt}}{P^{ElP}_{rt}} \right)^{\sigma^{ElP}}.
\end{aligned} \tag{B.13}$$

The only peculiar case that differs from the general CES equations written above concerns renewable electricity demand. Indeed, intermittent electricity supply is distributed to base and peak load according to the ratio r^{ElB}_{r} (see Section 2.3 for more details). For this specification to hold, the prices of intermittent electricity demand are fixed such that

$$\begin{aligned}
P^{ElIntB}_{i_i rt} &= P^{ElB}_{rt} \left(\frac{a^{ElIntB}_{i_i r} ElB_{rt}}{r^{ElB}_{r} Y_{i_i rt}} \right)^{\frac{1}{\sigma^{ElB}}}, \\
P^{ElIntP}_{i_i rt} &= \frac{(1 + tax^{P}_{i_i rt}) P^{Y}_{i_i rt} - r^{ElB}_{r} P^{ElIntB}_{i_i rt}}{1 - r^{ElB}_{r}}\,.
\end{aligned} \tag{B.14}$$

Then, quantities respect the equation

$$Y_{i_i rt} = ElIntB_{i_i rt} + ElIntP_{i_i rt}\,. \tag{B.15}$$

B.4 Factor market

Market clearing for full allocation

$$\begin{aligned} Lt_{Ltype,rt} &= \sum_{j \in Ltype} UnSkL_{jrt} \,, \\ SkL^{\text{TOT}}_{rt} &= \sum_j SkL_{jrt} \,, \\ Land^{\text{TOT}}_{rt} &= \sum_j Land_{jrt} \,, \\ Capital^{\text{TOT}}_{rt} &= \sum_j Capital_{jrt} \,. \end{aligned} \tag{B.16}$$

Endowments mobility (the case of perfect mobility)

Perfect mobility of land (if CET=0):

$$W^{Land}_{jrt} = W^{Land\text{TOT}}_{rt} \,. \tag{B.17}$$

Perfect mobility of capital under static mode:

$$W^{Capital}_{jrt} = W^{Capital\text{TOT}}_{rt} \,. \tag{B.18}$$

Land market (sluggish mobility)

Land is sluggish across sectors (CET),

$$\begin{cases} \max W^{Land\text{TOT}}_{rt} Land^{\text{TOT}}_{rt} = \sum_i W^{Land}_{irt} Land_{irt} \,, \\ \text{s.t.} \quad \left(Land^{\text{TOT}}_{rt}\right)^{1+\frac{1}{\sigma^{Land}}} = \sum_i b^{TE}_{ir} Land_{irt}^{1+\frac{1}{\sigma^{Land}}} \end{cases} . \tag{B.19}$$

The optimal supply for land is given as

$$Land_{irt} = b^{TE}_{ir} Land^{\text{TOT}}_{rt} \left(\frac{W^{Land}_{irt}}{W^{Land\text{TOT}}_{rt}} \right)^{\sigma^{Land}} . \tag{B.20}$$

Total land supply is

$$Land^{\text{TOT}}_{rt} = LandO^{\text{TOT}}_{rt} \left(\frac{W^{Land\text{TOT}}_{rt}}{P^U_{rt}} \right)^{\sigma^{Land\text{TOT}}_r} . \tag{B.21}$$

Endowments subvention and taxation

$$\begin{aligned} P^{Land}_{irt} &= W^{Land}_{irt} - P^U_{rt}\, sub^{Land}_{irt}\,, \\ P^{UnSkL}_{irt} &= \sum_{Ltype} W^{Lt}_{Ltype,irt} - P^U_{rt}\, sub^{UnSkL}_{irt}\,, \\ P^{SkL}_{irt} &= W^{SkL}_{irt} - P^U_{rt}\, sub^{SkL}_{irt}\,, \\ P^{Capital}_{irt} &= W^{Capital}_{irt} - P^U_{rt}\, sub^{Capital}_{irt}\,. \end{aligned} \tag{B.22}$$

Unskilled dual labor market

The demand for different types of labor follows the program (CET function),

$$\begin{cases} \min W^{UnskL\text{TOT}}_{rt}\, {UnskL^{\text{TOT}}}_{rt} = \sum_{Ltype} W^{Lt}_{Ltype,rt} Lt_{Ltype,rt}\,, \\ \text{s.t.} \quad {UnskL^{\text{TOT}}}_{rt}^{1+\frac{1}{\sigma^L}} = \sum_{Ltype} b^{Lt}_{Ltype,r} Lt^{1+\frac{1}{\sigma^L}}_{Ltype,rt}\,, \end{cases} \tag{B.23}$$

The optimal demand for unskilled labor of different types is given as

$$Lt_{Ltype,rt} = UnSkL^{\text{TOT}}_{rt} \left(\frac{W^{Lt}_{Ltype,rt}}{b^{Lt}_{Ltype,r} W^{UnSKl\text{TOT}}_{rt}} \right)^{\sigma^L} . \tag{B.24}$$

B.5 Trade and good market

Armington CES

There is an Armington specification between domestic and import demand:

$$\begin{cases} \min P^{DemTOT}_{ist}\, Dem^{\text{TOT}}_{ist} = P^D_{ist} D_{ist} + P^M_{ist} M_{ist}\,, \\ \text{s.t.} \quad Dem^{\text{TOT}}_{ist} = \left(a^D_{is} D_{ist}^{\frac{\sigma^{\text{ARM}}_i - 1}{\sigma^{\text{ARM}}_i}} + a^M_{is} M_{ist}^{\frac{\sigma^{\text{ARM}}_i - 1}{\sigma^{\text{ARM}}_i}} \right)^{\frac{\sigma^{\text{ARM}}_i}{\sigma^{\text{ARM}}_i - 1}} . \end{cases} \tag{B.25}$$

Thus,

$$\begin{aligned} D_{ist} &= Dem^{\text{TOT}}_{st} \left(\frac{a^D_{is} P^{DemTOT}_{st}}{P^D_{ist}} \right)^{\sigma^{\text{ARM}}_i}, \\ M_{ist} &= Dem^{\text{TOT}}_{st} \left(\frac{a^M_{is} P^{DemTOT}_{st}}{P^M_{ist}} \right)^{\sigma^{\text{ARM}}_i} . \end{aligned} \tag{B.26}$$

Import regions

Import demand is split between import regions:

$$\begin{cases} \min P^M_{ist} M_{ist} = \sum_r P^{\text{DEM}}_{irst} Dem_{irst}\,, \\ \text{s.t.} \quad M_{ist} = \left(\sum_r a^{\text{IMP}}_{irs} Dem_{irst}^{\frac{\sigma^{\text{IMP}}_i - 1}{\sigma^{\text{IMP}}_i}} \right)^{\frac{\sigma^{\text{IMP}}_i}{\sigma^{\text{IMP}}_i - 1}} \end{cases}. \tag{B.27}$$

The optimal imported goods demand is

$$Dem_{irst} = M_{ist} \left(\frac{a^{\text{IMP}}_{irs} P^M_{ist}}{P^{Dem}_{irst}} \right)^{\sigma^{\text{IMP}}_i}. \tag{B.28}$$

Good market

The equilibrium on good market decides the equilibrium good price. The production of good i in region r equals the sum of domestic demand for good i, total export of good i from region r, and supply of transportation in region r:

$$Y_{i,r,t} = \begin{cases} D_{irt} + \sum_s GnTC_{irst} Dem_{irst} & \text{if } i \notin Trt \\ D_{irt} + \sum_s GnTC_{irst} Dem_{irst} + Tr^{\text{Supply}}_{irt} & \text{if } i \in Trt \end{cases}. \tag{B.29}$$

We use a conversion coefficient between Y and production volume to translate trade flow in volume,

$$Trade_{irst} = Dem_{irst}\, YtoVol_{irt}\,. \tag{B.30}$$

FOB prices are production price with production tax and export tax,

$$P^{\text{FOB}}_{irst} = P^Y_{irs} GnMC_{irt} GnTC_{irst} (1 + tax^P_{irt})(1 + GnTax^{\text{EXP}}_{irst})\,. \tag{B.31}$$

CIF prices are FOB prices plus the cost of transportation,

$$P^{\text{CIF}}_{irst} = P^{\text{FOB}}_{irst} + GnMC_{irt} GnTC_{irst} \mu_{irs} P^{Tr}_{irst}\,. \tag{B.32}$$

Import prices from region r to s are CIF prices plus import tariffs,

$$P^{\text{DEM}}_{irst} = P^{\text{CIF}}_{irst} (1 + GnTrf_{irst})\,. \tag{B.33}$$

Prices of demand for domestic good i are production price with production tax,

$$P^D_{irt} = GnMC_{irt} P^Y_{irt} (1 + tax^P_{irst})\,. \tag{B.34}$$

World price of good i is the average CIF price of all export regions,

$$\ln(P_{it}^{World} P_i^{WO}) \sum_{rs} Trade_{irst} = \sum_{rs} Trade_{irst} \ln(P_{irst}^{\text{CIF}}\, YtoVol_{irt})\,. \tag{B.35}$$

B.6 International transportation

Transportation demand

Merchandise transportation demand equals demand of transportation per unit of volume and the bilateral trade,

$$Tr_{jrst} = \mu_{jrs} GnTC_{jrst} GnMC_{jrt} Dem_{jrst}\,. \tag{B.36}$$

Merchandise transportation demand per mode follows Cobb-Douglas formation,

$$\begin{cases} \min P_{jrst}^{Tr} Tr_{jrst} = \sum_i P_{it}^{\tilde{T}r} \tilde{T}r_{ijrst}\,, \\ \text{s.t.} \quad Tr_{jrst} = \prod_i \tilde{T}r_{ijrst}^{a_{ijrs}^{Tr}}\,. \end{cases} \tag{B.37}$$

By solving the above program, optimal demand for transportation per mode is

$$\tilde{T}r_{ijrst} = \frac{a_{ijrs}^{Tr} P_{jrst}^{Tr} Tr_{jrst}}{P_{it}^{\tilde{T}r}}\,. \tag{B.38}$$

Price of merchandise transportation demand is

$$P_{jrst}^{Tr} = \prod_i {P_{it}^{\tilde{T}r}}^{a_{ijrs}^{Tr}}\,. \tag{B.39}$$

Transportation supply

World merchandise transportation is a Cobb-Douglas aggregation of transportation supply per mode,

$$World_{it}^{Tr} = c_i^{Tr} \prod_r {Tr_{irt}^{\text{Supply}}}^{a_{ir}^{TrSupply}}\,. \tag{B.40}$$

Merchandise transportation supply by region r is

$$Tr_{irt}^{\text{Supply}} = \frac{a_{ir}^{TrSupply} P_{it}^{\tilde{T}r} World_{it}^{Tr}}{P_{i\in Trt,rt}^{Y}(1 + tax_{i\in Trt,rt}^{P})}\,. \tag{B.41}$$

Transportation market clearing

Clearing for merchandise transportation market:

$$World_{it}^{Tr} = \sum_{jrs} \tilde{T}r_{ijrst}\,. \tag{B.42}$$

B.7 Imperfect competition and generalized costs

Generalized marginal cost

Perfect competition:

$$GnMC_{irt} = 1\,. \tag{B.43}$$

Imperfect competition:

$$GnMC_{irt} = N_{irt}^{\frac{1}{1-\sigma_i^{\text{VAR}}}} \frac{\sigma_i^{\text{VAR}}}{\sigma_i^{\text{VAR}} - 1}\,. \tag{B.44}$$

Number of firms is determined as

$$N_{irt} = \left(\frac{fc_{ir}(\sigma_i^{\text{VAR}} - 1)}{Y_{irt}}\right)^{\frac{1-\sigma_i^{\text{VAR}}}{\sigma_i^{\text{VAR}}}}\,. \tag{B.45}$$

Value to volume

Perfect competition:

$$YtoVol_{irt} = 1\,. \tag{B.46}$$

Imperfect competition:

$$YtoVol_{irt} = N_{irt}^{\frac{1}{1-\sigma_i^{\text{VAR}}}}\,. \tag{B.47}$$

Generalized iceberg trade cost

$$GnTC_{irst} = 1 + tCostTF_{irst} + tax_{irst}^{\text{SER}} shareNTM_{irs}^{tCost} + NTM_{irst} shareNTM_{irs}^{tCost}\,. \tag{B.48}$$

Generalized tariff

$$GnTrf_{irst} = Tariff_{irst} + NTM_{irst} shareNTM_{irs}^{Tariff}\,. \tag{B.49}$$

Generalized export tax

$$GnTax_{irst}^{\text{EXP}} = tax_{irst}^{\text{EXP}} + tax_{irst}^{\text{MFA}} + shareNTM_{irs}^{tax^{\text{EXP}}}(NTM_{irst} + tax_{irst}^{\text{SER}})\,. \tag{B.50}$$

B.8 Income and tax revenue

Production taxes revenues

$$RevTax^{P}_{irt} = tax^{P}_{irt} P^{Y}_{irt} Y_{irt} GnMC_{irt}\,. \tag{B.51}$$

Export taxes revenues

$$Revtax^{\text{EXP}}_{irt} = P^{Y}_{irt}(1 + tax^{P}_{irt}) GnMC_{irt} \sum_{s} (tax^{\text{EXP}}_{irst} + tax^{\text{MFA}}_{irst}) GnTC_{irst} Dem_{irst}\,. \tag{B.52}$$

Tariff revenues

$$RevTariff_{ist} = \sum_{r} Tariff_{irst} P^{\text{CIF}}_{irst} Dem_{irst}\,. \tag{B.53}$$

Rents from NTMs

$$\begin{aligned} RevNTM_{st} = & \sum_{i,r} P^{\text{CIF}}_{irst}(GnTrf_{irst} - Tariff_{irst}) Dem_{irst} \\ & + \sum_{i,r'} GnMC_{ist} P^{Y}_{ist}(1 + tax^{P}_{ist})(GnTax^{\text{EXP}}_{isr't} \\ & - tax^{\text{EXP}}_{isr't} - tax^{\text{MFA}}_{isr't}) GnTC_{isr't} Dem_{isr't}\,. \end{aligned} \tag{B.54}$$

Final consumption tax revenue

$$\begin{aligned} RevTax^{C}_{i,s,t} = & P^{DemTOT}_{ist}(tax^{C}_{ist} C_{ist} + tax^{KG}_{ist} KG_{ist} \\ & + \sum_{j} tax^{IC}_{ijst} IC_{ijst} + \sum_{j} tax^{EIC}_{ijst} EIC_{ijst})\,. \end{aligned} \tag{B.55}$$

GHG tax revenue

$$\begin{aligned} RevTax^{GHG}{}_{rt} = & \sum_{g,j \notin TrT} (tax^{GHG}{}_{grt} - tax^{fGHG}_{gjrt}) EmF^{Y}_{gjr} P^{U}_{rt} GHG_{gjrt} \\ & + \sum_{g,j \in TrT} (tax^{GHG}{}_{grt} - tax^{fGHG}_{gjrt}) EmF^{Y}_{gjr} P^{U}_{rt} \left(1 - \frac{Tr^{\text{Supply}}_{jrt}}{Y_{jrt}}\right) GHG_{gjrt} \\ & + \sum_{g,e,j \notin TrT} (tax^{GHG}{}_{grt} - tax^{fGHG}_{gjrt}) EmF^{IC}_{gejr} P^{U}_{rt} AgC_{ert} GHG^{IC}_{gejrt} \\ & + \sum_{g,e,j \in TrT} (tax^{GHG}{}_{grt} - tax^{fGHG}_{gjrt}) EmF^{IC}_{gejr} P^{U}_{rt} AgC_{ert} \left(1 - \frac{Tr^{\text{Supply}}_{jrt}}{Y_{jrt}}\right) GHG^{IC}_{gejrt} \\ & + \sum_{g,e} tax^{GHG}{}_{grt} EmF^{C}_{ger} P^{U}_{rt} AgC_{ert} C_{ert}\,. \end{aligned} \tag{B.56}$$

Total revenue

$$\begin{aligned}
RevTax_{rt} = & \sum_i (RevTax^{P}_{irt} + Revtax^{\text{EXP}}_{irt} + RevTariff_{irt} \\
& + RevTax^{C}_{irt}) + RevTax^{GHG}{}_{rt}\,, \\
Rev_{r,t} = & \sum_i \Big[P^{NatRes}_{irt} NatRes_{irt} ResV_{it} + P^{Land}_{irt} Land_{irt} \\
& + P^{SkL}_{irt} SkL_{irt} + P^{UnSkL}_{irt} UnSkL_{irt} \\
& + \sum_s P^{Capital}_{ist} K_{irst} \\
& + \sum_s (P^{\text{CIF}}_{irst} rente_{irst} - P^{\text{CIF}}_{isrt} rente_{isrt}) \Big] \\
& + RevTax_{rt} + RevNTM_{rt}\,, \\
I_{rt} = & (1 - Sav_{rt}) Rev_{rt}\,.
\end{aligned} \tag{B.57}$$

World GDP

$$WGDP_t = \sum_r GDP^*_{rt}\,. \tag{B.58}$$

B.9 Investment

Investment behavior

Investment by region r in region s is

$$Inv_{irst} = B_{rt} a_{irs} Capital_{ist} \exp\left[\alpha \left(\frac{W^{Capital}_{ist}}{P^{InvTOT}_{st}} - \delta_r\right)\right]. \tag{B.59}$$

Total investment in region s is

$$Inv^{\text{TOT}}_{st} = \sum_{i,r} Inv_{irst}\,. \tag{B.60}$$

Current account closure

$$Sav_{st} Rev_{st} = \sum_{i,r} P^{InvTOT}_{st} Inv_{irst} + WGDP_t CA_{st}\,. \tag{B.61}$$

B.10 Capital and dynamics

Capital dynamics

The capital dynamics for capital invested by r in s is

$$K_{irst} = K_{irs,t-1}(1 - \delta_r) + Inv_{irst}\,. \tag{B.62}$$

The capital stock in region s is

$$Capital_{ist} = \sum_r K_{irst} \,. \tag{B.63}$$

National accounts

Value of total demand in region r is the sum of imported demand and domestic demand,

$$DemNA_{irt} = P^D_{irt} D_{irt} + \sum_s P^{Dem}_{isrt} Dem_{isrt} \,. \tag{B.64}$$

Price of total demand:

$$P^{DemNA}_{irt} = \frac{DemNA_{irt}}{DemNA^*_{irt}} \,. \tag{B.65}$$

Consumption price:

$$P^{CNA}_{irt} = P^{DemNA}_{irt} (1 + tax^C_{irt}) \,. \tag{B.66}$$

Consumption:

$$P^{CNA}_{irt} CNA_{irt} = P^C_{irt} C_{irt} \,. \tag{B.67}$$

Capital good price:

$$P^{KGNA}_{irt} = P^{DemNA}_{irt} (1 + tax^{KG}_{irt}) \,. \tag{B.68}$$

Capital good:

$$P^{KGNA}_{irt} KGNA_{irt} = P^{KG}_{irt} KG_{irt} \,. \tag{B.69}$$

Total GDP:

$$\begin{aligned} GDP_{rt} = {} & \sum_i P^{KGNA}_{irt} KGNA_{irt} + \sum_i P^{CNA}_{irt} CNA_{irt} \\ & + \sum_{i \in Trt} P^Y_{irt} (1 + tax^P_{irt}) Tr^{\text{Supply}}_{irt} \\ & + \sum_{i,s} P^{\text{FOB}}_{irst} Dem_{irst} - \sum_{i,s} P^{\text{CIF}}_{isrt} Dem_{isrt} \,. \end{aligned} \tag{B.70}$$

TFP

GDP dynamic for TFP computation in baseline:

$$GDP^*_{rt} = g^{GDP}_{rt} GDP^*_{r,t-1} \,. \tag{B.71}$$

Sectoral TFP:

$$TFPJ_{irt}\, TFP_{rt} = \begin{cases} TFPi_{irt} & \text{if } i \in \text{Agri} \,, \\ (1 + \phi^p_{irt})\, TFPJ_{ir,t-1}\, TFP_{rt} & \text{if } i \notin \text{Agri} \,. \end{cases} \tag{B.72}$$

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$$\sum_r GDP^*_{rt} = WGDP_t \,. \tag{B.73}$$

B.11 GHG emissions

Accounting

GHG emission value from energy intermediate consumption,

$$GHG^{IC}_{geirt} = a^{GHGIC}_{geir} \times \begin{cases} Coal_{irt} & \text{if} \quad e = \text{“coal”}\,, \\ Oil_{irt} & \text{if} \quad e = \text{“oil”}\,, \\ Gas_{irt} & \text{if} \quad e = \text{“gas”}\,, \\ Petroleum_{irt} & \text{if} \quad e = \text{“petroleum”}\,, \\ Electricity_{irt} & \text{if} \quad e = \text{“elec”}\,. \end{cases} \tag{B.74}$$

GHG emissions from firms,

$$EmGHG^{IC}_{geirt} = EmF^{IC}_{geir} GHG^{IC}_{geirt} AgC_{ert} \,. \tag{B.75}$$

GHG emissions from households,

$$EmGHG^{H}_{gert} = EmF^{C}_{ger} C_{ert} AgC_{ert} \,. \tag{B.76}$$

GHG emissions from production,

$$EmGHG^{Y}_{girt} = EmF^{Y}_{gir} GHG_{girt} \,. \tag{B.77}$$

GHG emissions by region,

$$EmGHG_{grt} = \sum_{ei} EmGHG^{IC}_{geirt} + \sum_{e} EmGHG^{H}_{gert} + \sum_{i} EmGHG^{Y}_{girt} \,. \tag{B.78}$$

GHG emissions from transport,

$$EmGHG^{\text{Freight}}_{g,TrT,r,t} = \left[\sum_i EmGHG^{IC}_{g,i,TrT,r,t} + EmGHG^{Y}_{g,TrT,r,t} \right] \frac{Tr^{\text{Supply}}_{TrT,r,t}}{Y_{TrT,r,t}} \,. \tag{B.79}$$

Carbon policy

Constraint on GHG emissions (when Cap and Trade and not transport sector),

$$EmGHG_{grt} = GHGCap_{grt} \,. \tag{B.80}$$

Constraint on GHG emissions (when intensity cap and not transport sector),

$$EmGHG_{grt} = GHGICap_{grt} GDP^{*}_{rt} \,. \tag{B.81}$$

Carbon tax when exogenous,

$$tax^{GHG}{}_{grt} = GHGTax_{grt} \,. \tag{B.82}$$

B.12 Energy Volume

Gross Energy consumption by intermediate consumption (Mtoe):

$$E^{IC}_{ejrt} = \epsilon^{IC}_{ejr} AgC_{ert} (EIC_{ejrt} + IC_{ejrt}) \,. \tag{B.83}$$

Gross Energy consumption by households (Mtoe):

$$E^{C}_{ert} = \epsilon^{C}_{er} AgC_{ert} C_{ert} \,. \tag{B.84}$$

Energy produced (Mtoe):

$$E^{Y}_{ert} = \epsilon^{Y}_{er} YtoVol_{ert} Y_{ert} \,. \tag{B.85}$$

Final energy consumption (Mtoe):

$$E^{D}_{ert} = \epsilon^{D}_{er} AgDem_{ert} YtoVol_{ert} D_{ert} \,. \tag{B.86}$$

Traded energy (Mtoe):

$$E^{Dem}_{erst} = \epsilon^{Dem}_{ers} AgDem_{ert} YtoVol_{ert} Dem_{erst} \,. \tag{B.87}$$

Total energy demanded by region s (Mtoe):

$$E^{Dem\text{TOT}}_{est} = E^{D}_{est} + \sum_{r} E^{Dem}_{erst} \,. \tag{B.88}$$

Total energy consumed in region r (Mtoe):

$$EC_{ert} = E^{C}_{ert} + \sum_{j} E^{IC}_{ejrt} \,. \tag{B.89}$$

Quantity conservation

Accounting between energy production and addressed demand (Mtoe):

$$E^{Y}_{ert} = E^{D}_{ert} + \sum_{s} E^{Dem}_{erst} \,. \tag{B.90}$$

Accounting between energy consumed and demanded (Mtoe):

$$EC_{ert} = E_{ert}^{Dem\text{TOT}}\,. \tag{B.91}$$

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