A Dynamic Path to a Low Carbon Economy

Cecilia Bellora* Lionel Fontagné† Yu Zheng‡

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Abstract

Achieving the climate goals set by the Paris Agreement requires a transition to low-carbon energy and therefore the structural transformation of our economies. Our reference is the long-term trajectory of the world economy based on the macroeconomic projections of the MaGE 3.1 model including demographics, education, life-cycle savings, technological catch-up, energy efficiency and current account balance of each country by 2050. We incorporate these projections of current account balance, investment and savings rates, labor force, skills, and GDP trajectories as exogenous variables into a dynamic sectoral CGE model of the world economy characterized by imperfect competition, an electricity mix including renewables, and emissions of all greenhouse gases. This reference trajectory of the world economy is then compared to a scenario imposing the updated unconditional Paris Nationally Determined Contributions (NDCs). We consider that the European Union (EU) has adjusted its cap-and-trade market by introducing a border carbon adjustment, while other countries committed to reducing their emissions also stick to their unconditional NDCs. We quantify the level explicit or implicit taxation of carbon needed to meet these targets, the shift in demand and investment to lower-emitting sectors, and the extent and direction of leakage.

Key Words: International Trade, Climate Change.

JEL Codes: F14, F13, F17, Q56.

*OECD

†Bank of France, CEPII and PSE. Correspondence: Banque de France, 31 rue Croix des Petits-Champs 75049 PARIS cedex 01 (France). Email: lionel.fontagne@banque-france.fr.

‡CEPII, 20 avenue de Ségur 75007 Paris. Email: yu.zheng@cepii.fr.

Introduction[1]

Achieving the objective set out by the Intergovernmental Panel on Climate Change (IPCC) of global warming below 2 degrees Celsius above the pre-industrial average requires a transition to low-carbon energy and, more generally, a profound structural transformation of our economies.[2] Then, tacking stock of the present level of ambition of the different countries, our question is "How will the implementation of the commitments made in the NDCs transform the economies engaged in mitigating their emissions?". Studying these changes requires first of all a detailed "business-as-usual" long-term trajectory of the economies. It is then on the basis of such a reference that the impacts of climate policies, and more generally of any long-term public policy, on the structure of economies can be studied through a counterfactual approach. We therefore proceed in two steps. First, we construct a long-term trajectory for the global economy up to 2040. Second, we analyse in detail the impacts of a transition to a more sustainable, less greenhouse gas (GHG) intensive economy, in line with the commitments made in the Paris Agreement and updated in November 2021, during the COP 26, with a focus on the "Fit for 55 package" of the European Commission.

The long-term trajectory is constructed on the basis of the macroeconomic projections of the MaGE model (Fouré, Bénassy-Quéré & Fontagné 2013). This three-factor model (labor, capital and energy) details the working population by education level, age group and gender. It represents a dual process of international convergence of technological levels and energy efficiency. It includes a life cycle determining the level of savings according to the demographic pyramid and a Feldstein-Horioka mechanism determining the international mobility of capital. It consistently projects, for a sample of 170 countries, the GDP, the savings rate, the current account, and the energy efficiency up to 2050. In the following, we use the latest projections (2018-2050), based on up-to-date estimates (Fontagné, Perego & Santoni 2021).

These projections are the basis for the long-term trajectory of a dynamic general equilibrium model featuring renewable energy in power generation and emissions of GHG. To proceed, we use the MIRAGE-POWER model. It is a global, dynamic, multi-sectoral and multi-regional model, featuring a detailed representation of energy use and electricity activities. Specifically, electricity is generated from multiple sources including renewables, nuclear, coal, oil, and gas. The regional electricity producer provides aggregate electricity for intermediate consumption and households. Electricity as such

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[2] This initial target has been reinforced in the 2022 IPCC report stating that "climate resilient development prospects are increasingly limited if current greenhouse gas emissions do not rapidly decline, especially if 1.5 degree Celsius global warming is exceeded in the near-term" (IPCC (2022), summary for policy makers, p.35). The Paris agreement states aims to "substantially reduce global greenhouse gas emissions to limit the global temperature increase in this century to 2 degrees Celsius while pursuing efforts to limit the increase even further to 1.5 degrees."

can also be traded. Furthermore, as it is standard in energy-oriented models, energy is not considered as an intermediate consumption but directly substitutes with capital in the production function. In addition, energy is subject to independent productivity improvements, specifically calibrated. GHG emissions due to both energy use (carbon dioxide) and production processes (methane, nitrous oxide and fluorinated gases) are explicitly reported. The model also accounts for trade policies, based on highly disaggregated databases of the equivalents of tariff and non tariff protection, as well as climate policies, in particular cap and trade mechanisms. The model embeds an improved representation of electricity mix and energy mix that, coupled to the results on emissions, allows to discuss in details the energy transition from brown sources to green sources through climate change policy.

To build the business as usual (BAU) reference scenario in line with the macroeconomic projections, MIRAGE-POWER integrates the current account targets, the investment and savings rates, the participation rates and skills and the GDP trajectories as projected by MaGE. It uses the same series as MaGE for the exogenous variables, i.e.demography from the UN central scenario as well as the international energy prices form the International Energy Agency (IEA). A first simulation is carried out to reconcile the two models, in which the Total Factor Productivity (TFP) is considered as an endogenous variable. Once the TFP trajectory is solved, in the counterfactual simulations, the TFP becomes exogenous again, imposed on MIRAGE, the GDP becoming endogenous. This BAU integrates the Brexit, an important issue when it comes to the functioning of the European Union (EU) Emissions Trading System (ETS).

The long-term trajectory thus constructed, without any policy shocks with respect to the base year of the GTAP 10.1 POWER (2014), is of interest in itself. It details at the sector level and for each region the state of the World economy to 2050 based on the macroeconomic projections. It answers the following question: "Given what we know about the functional relationships between observables, what should be the economic trajectory of the different countries, all other things being equal, when their demographics, their education effort, and the price of energy vary at different rates over time?" MIRAGE-POWER enriches the information taken from MaGE with sectoral information (trajectories of each sector relative to the others within each economy), with the composition of the energy mixed used by each country, with information on GHG emissions, at the sectoral and regional level and information concerning future trade patterns. Emission data are taken from the GTAP-E database and the satellite data on non-CO_2 emissions also provided by GTAP.

The second step of our work is to compare this long-term trajectory with a counterfactual scenario in which the EU and the subset of countries actually engaged in abating unconditionally their emissions meet their NDCs as of the COP26. It would be excessively pessimistic to assume that only the EU is likely to be able to implement ambitious climate policies. But it would also be particularly optimistic to consider that all countries that have made commitments under the Paris Agreement will meet them. The choice of which countries meet their commitments is consequently an important issue, because it determines the cost that each country has to bear, given a given climate ambition, as well as, of course, the global level of emissions. We assume that conditional NDCs will not be reached, as opposed to unconditional ones.

We translate all the considered NDCs, whether formulated in absolute or in intensity terms or formulated with respect to a business as usual reference, in a relative reduction with respect to 2014, the base year in our simulations. We then apply this reduction linearly from 2014 to the horizon retained in NDCs. If this horizon occurs before 2040, which is the case for the majority of the commitments considered, we keep the commitment unchanged until 2040. Technically speaking, the commitments translate in a yearly cap on GHG emissions, imposed to each committed region of our regional aggregation, and the model then endogenously adjusts the level of a tax on GHGs – an implicit price of carbon – to meet this target.

large countries with a national cap-and-trade market in place in 2022 deserve a special treatment. The EU ETS put in place in 2005 its EU-ETS market. In order to reach the target of −55% of economy-wide emissions by 2030 set in the EU new NDCs (i.e. the "Fit for 55 package"), we consider two carbon taxes in the EU: one specific to the ETS, and one that applies to all other sectors and to final consumers. The cap imposed to the emissions of the sectors covered by the ETS is the one proposed by the Commission in July 2021, i.e. 61% in 2030 with respect to 2005. Our modelling integrates the phasing out of free allowances on the ETS market as the carbon Border Adjustment Mechanism is progressively phased in over the 2026-35 period. The level of the tax supported by sectors not covered by the ETS and by households is set to achieve the Paris target, conditional on the reductions undertaken in the ETS sectors. China had also a cap-and-trade market in place since 2021. It currently covers only emissions by electricity generation but is expected to be progressively extended to other sectors (and should have been extended already although it has been postponed for technical reasons pertaining to reporting). we make the assumption that the same set of industries as in the EU will be covered and settle this coverage from 2021 onwards by sake of simplicity. The cap is defined by translating overall Chinese NDCs to the concerned sectors.

The paper provides detailed results about the following outcomes: (i) the level of the carbon taxation required to meet the targets as set in the most recent NDCs, (ii) the path of energy transition as the change in the energy mix and electricity mix, in particular, the share of renewable energy, required to achieve the target emission reductions (iii) the size of the demand and investment displacement towards the sectors that emit less, (iv) the size and direction of leakages caused by the presence of large free riders and (v) a quantification of the changes in comparative advantages across countries and the resulting impacts on trade.

The remaining of the paper is organised as follows. The first section presents MaGE, the growth model used for macroeconomic projections. The second section presents MIRAGE-POWER, the General Equilibrium model. The third section presents the results of our scenario implementing the commitments of the COP26 and of the Fit for 55 package. The last section concludes.

1 The growth model

Building on the literature tackling long-term economic projections for the world economy ((Duval & de la Maisonneuve 2010, Johansson, Guillemette, Murtin, Turner, Nicoletti, de la Maisonneuve, Bagnoli, Bousquet & Spinelli 2013, Cette, Lecat & Ly-Marin 2017) MaGE relies on the standard framework of conditional convergence (Barro & Sala-i Martin 2004) and growth accounting (Easterly & Levine 2001) adapted to a three-factor model featuring energy. A constant nested elasticity of substitution function between energy and a (Cobb-Douglas) bundle of the two other primary factors – capital and labour – follow the preferred nesting of van der Werf (2008) is used. This nesting reads:

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

with $Y_{i,t}$ the GDP of country i at year t; A the TFP of the capital-labour bundle and B the energy efficiency.[3]

This approach is similar to the one adopted by the Massachusetts Institute of Technology Emissions Prediction and Policy Analysis model – EPPA (Paltsev, Reilly, Jacoby, Eckaus, McFarland, Sarofim, Asadoorian & Babiker 2005). This allows us to differentiate between two different types of productivity, TFP (of labour and capital), and energy efficiency. Each functional relationship in the model is estimated on historical data going back to 1950 (for some series) and projected over the long term under the assumption that the behaviour and dynamics observed in the past will remain stable. This is a conservative assumption, especially for the shift in time of the technological frontier in terms of energy efficiency, insofar as the innovative effort in green technologies should rise with global warming and the price of carbon.

[3] α is set to 0.3 and σ, recovered from MIRAGE, is set to 0.25.

Substituting the optimality condition for energy, E in Eq. 1, GDP is projected as:[4]

$$Y_{i,t} = \left[1 - \left(\frac{B_{i,t}}{p_{E,t}}\right)^{\sigma-1}\right]^{\frac{\sigma}{1-\sigma}} A_{i,t} K_{i,t}^{\alpha} L_{i,t}^{1-\alpha} \tag{2}$$

MaGE departs from research aimed at translating Shared Socioeconomic Pathways (SSP) into economic scenarios.[5]. There is only one a reference path of the world economy: MaGE can of course be used as a starting point for the construction of scenarios by amending certain parameters or exogenous factors (Fontagné, Fouré & Keck 2017, Dellink, Chateau, Lanzi & Magné 2017) as to translate their narrative into a quantitative modelling.[6]

Concerning labour, we start from the UN central demographic scenario. The labour force consists of cohorts at five-year age intervals, and is defined as the active fraction of the population in each. We distinguish between male and female participation, the latter being a function of secondary and tertiary education. Educational attainment is a catch up process, projected for each level of education as a function of the speed of regional convergence with respect to the distance from the leader (the US in the data). The trajectory of the two types of labour in each region are imposed to the GE model.

Capital is accumulated in MaGE following a permanent inventory process with a depletion rate of 6% (same calibration as in MIRAGE-POWER). Gross investment is a function of GDP and of the investment rate, which differs from the savings rate due to international capital mobility (Feldstein & Horioka 1980). This savings rate is projected according to the life-cycle hypothesis (Masson, Bayoumi & Samiei 1998). In such framework the current account of each country at each date is simply the difference between savings and investments: it taken as an exogeneous variable in the first step of MIRAGE-POWER.

Two variables remain to be defined: the TFP of the labour-capital bundle and the energy efficiency. TFP projections in MaGE are based on the estimation of a catch-up model (Nelson & Phelps 1966), in which the speed of convergence to the efficiency frontier is driven by the secondary and tertiary education attainment of the catching country. This TFP helps in projecting the GDP in MaGE but is retrieved in the first step of MIRAGE-POWER in order to make the GE and the macro model consistent.

Differently, energy efficiency $B_{i,t}$ is given fy the fo.c. of a firm maximization problem: as suggested by Eq. 1, $B_{i,t}$ is a function of $E_{i,t}$ and$Y_{i,t}$ (the inverse energy intensity of the value added), of the

[4]GDP of oil-producing countries is projected net of oil rents.

[5]See the projections of the International Institute for Applied Systems Analysis (IIASA) `https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about`

[6]The Econmap database provides the MaGE projections of the baseline scenario used here, as well as five SSP scenarios.

price of energy, and of the elasticity of substitution σ. $B_{i,t}$ enters as a component of the energy productivity of MIRAGE-POWER, combined with the relative price of energy with respect to capital, the elasticity of substitution between capital and energy, and the TFP of the broad sectors (agriculture, manufacturing, services). Energy efficiency is retrieved using a double catch-up model with respect to the energy-efficiency frontier and the income frontier. For the projections at each time point, this double catch-up approach also includes the average energy efficiency of the preceding five-year window in such a way as to capture the momentum of gradual adoption of more energy efficient technologies.

The last variable of Eq.2 needed for projection is the price of energy: it is taken from the projections of the IEA.[7]

2 The General Equilibrium model

MIRAGE-POWER is a multi-sector and multi-region computable general equilibrium model of the world economy that aims to assess the impact of trade policies and the interactions between trade and climate change. It innovates by featuring renewable energy in electricity generation and an improved representation of GHG emissions.[8]

2.1 Overall setup

In the model, firms interact either in a monopolistic competition (a number of identical firms in each sector and region compete one with another and charge a markup over marginal costs) or in a perfect competition framework (a representative firm by sector and region charges the marginal cost), depending on the sector that is considered. Production combines value-added plus energy and intermediate consumption, while demanding five primary factors (labor with two different skill levels, capital, land, natural resources), fully employed.

In each region, a representative consumer gathers households and the government. It maximizes its utility under its budget constraint. This representative agent saves a part of her income and spends the rest on commodities, according to a LES-CES functional form.

MIRAGE-Power incorporates the detailed electricity power generation specifications. In particular, electricity is generated from multiple sources including renewables, nuclear, coal, oil, and gas. The regional electricity producer provides aggregate electricity for intermediate consumption and

[7]EIA data on Real Petroleum prices: Crude oil, Brent Spot, Reference price AEO 2020-2019 /b from 2019 to 2050

[8]MIRAGE stands for Modelling International Relationships in Applied General Equilibrium. MIRAGE-POWER is the extension of MIRAGE-e documented in Fontagné, Fouré & Ramos (2013) that did not differentiate electricity generation activities from different sources, and that did not consider GHGs other than carbon dioxyde produced by burning fossil energies. The initial version of MIRAGE, which did not feature emissions of GHG, is documented in Decreux & Valin (2007).

households. Electricity as such can also be traded. Beyond electricity generation, further features are specialized for trade policy analysis with a focus on energy. In this standard energy-oriented model, energy is not considered as an intermediate consumption but directly substitutes with capital in the production function. In addition, energy is subject to independent productivity improvements, specifically calibrated.

Finally, MIRAGE-POWER is a recursive dynamic model: agents optimize their choices intra-temporally and the model is solved each year until the last year considered in the simulation. A putty-clay formulation captures the rigidity in capital reallocation across periods: the stock of capital is immobile, while investments are allocated each year across sectors according to relative return rates. In other words, structural adjustments result from the inertial reallocation of the stock of capital via depreciation and investment.

The model is calibrated using the GTAP 10.1 POWER database, that features a decomposition of electricity transmission and electricity generation activities that is consistent with GTAP 10.1 standard database. The 10.1 release of the GTAP-POWER database features 2014 as the last reference year. It represents the world economy considering 76 sectors in each of the 147 regions of its geographic decomposition. We aggregate this data into 23 sectors and 28 regions or countries (see Tables A1 and A2 in the Appendix for the detailed aggregations).

2.2 The dynamic baseline in MIRAGE-POWER

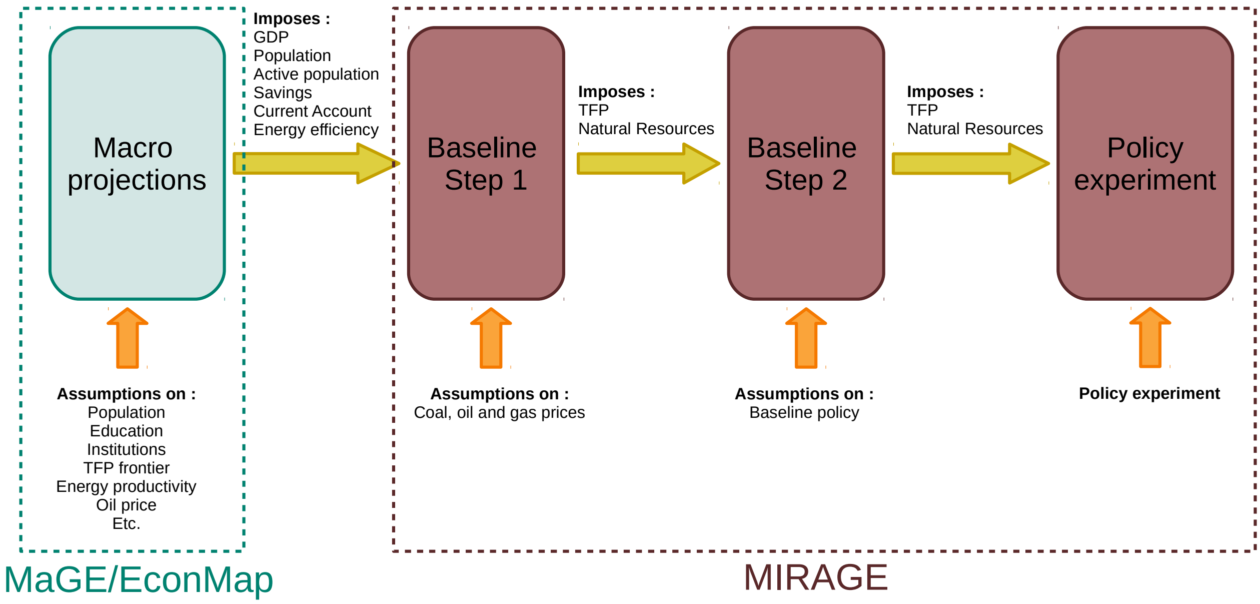
We build the BAU using the macroeconomic projections of the MaGE model (disseminated as the Econmap 3.1 database). A series of outputs of MaGE are imposed to MIRAGE-POWER, while a series of exogenous variables are common to the two models. The exogeneous variables common to the two models are: demography from the UN central scenario by age bin of five years and the oil price as projected by the IEA. The GE model also embarks the projected price of gas and coal (IEA projections) as exogeneous variables in this first step. Availability of natural resources is made consistent with the demand for energy in the MIRAGE-POWER and the prices of energy set as exogeneous. These stocks of natural resources are exogeneous in the second step, described below. Concerning MaGE outputs, MIRAGE-POWER imports from MaGE, for each year and country, the GDP , the labour force (participation rate by gender × demography), the education level (transformed into the two level of skills of GTAP), the volume of investment (to be allocated across sectors), the energy efficiency and the current account. Endogenous TFP in MIRAGE-POWER makes the two models consistent at each date, in a first step, recursively. More precisely, the endogenous variable is the TFP in the manufacturing sector conditional on the agricultural TFP (exogenous) and on a constant difference in TFP between manufacturing and services. This first step is coined "Baseline Step 1" in Figure 1.

The second step of the construction of the BAU is to enforce different policies in MIRAGE-POWER, while keeping TFP and natural resources now exogenous, at the levels set in the first step. Consequently, GDP, investment, energy prices are now endogenized. In this second step, we also represent in a stylized way a soft Brexit, since it plays an important role in the decoupling of the UK climate policy from the one of the European Union. [9]

Noticeably, neither the Paris agreement nor the ETS are present in this baseline.[10]

The third step is the policy experiment. Countries that have introduced a national carbon market by the end of 2021 are assumed to be sufficiently committed to mitigating their GHG emissions to meet their NDC unconditional targets (as of COP26). Such treatment indeed introduces a constraint in terms of geographic aggregation of the model: regions of the world economy must be consistent in terms of their NDCs (and in terms of their actual implementation).[11] EU 27 and China deserves a special treatment in our third step, as far as their climate policies are concerned.

Figure 1: The three steps in MIRAGE-POWER



[9]We represent a soft Brexit by leaving the tariffs applied by the UK and the EU unchanged, while increasing their bilateral NTMs to halve the preferential access of the UK to the EU market, and reciprocally. At this stage, we do not consider any other update in trade policies after 2014.

[10]On may be concerned by the absence of the EU ETS from the baseline. This is on purpose, as we are interested in the economic impact of the Fit for 55 package. In 2014 the price of allowances on the EU ETS was close to zero (e.g. 4.59 euro en January 6th and most of the allowances were free, with the exception of electricity generation.

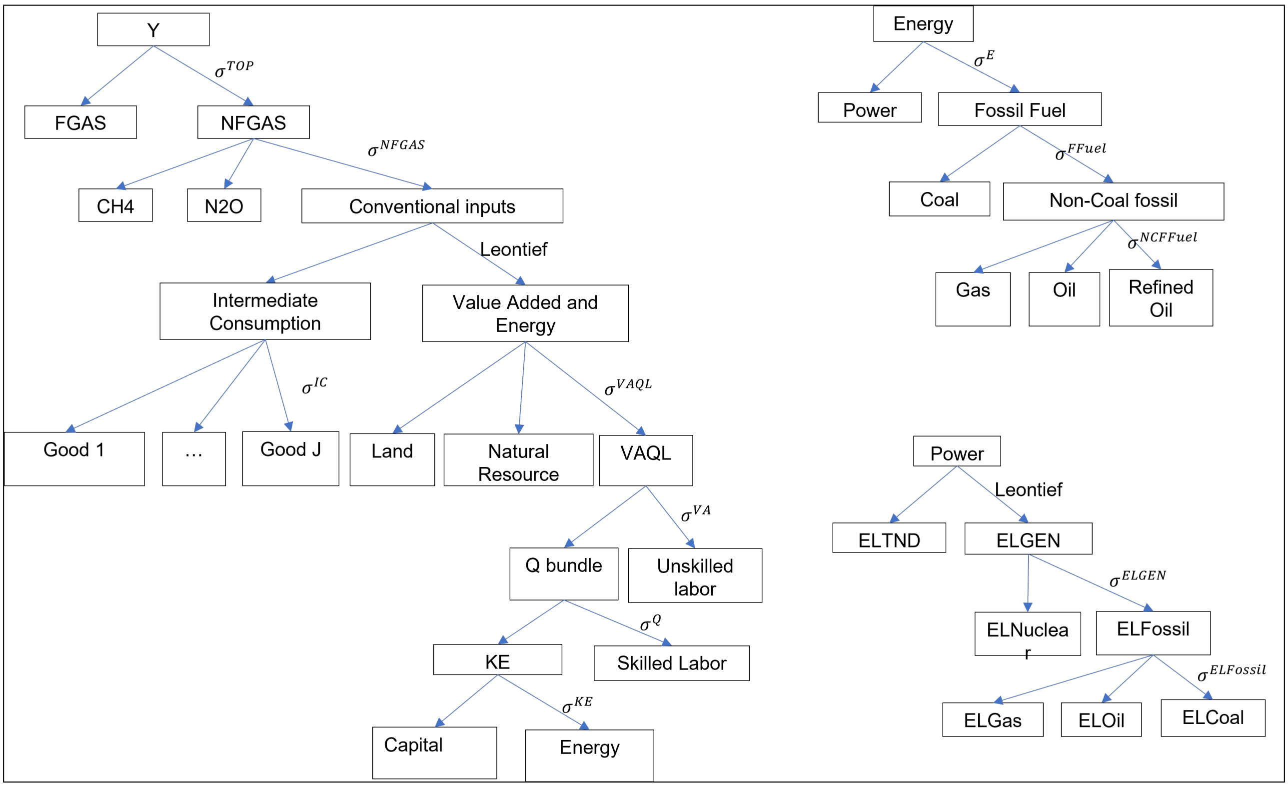
[11]The regional aggregation in GTAP 10.1 imposes slight departures from this consistency for certain "Rest of" regions. We also aggregated a couple of small size economies to larger groups for computational purposes.

2.3 The GHG emissions

To account for GHGs emissions, MIRAGE-e explicitly considers the consumption of five energy goods (electricity, coal, oil, gas, refined petroleum). In firms' consumption, the bundle of these five goods substitutes with capital, in the value added structure, instead of substituting with intermediate consumptions. Within the energy bundle, oil, gas and refined petroleum are more substitutable than coal or electricity. To avoid unrealistic results, energy production sectors other than electricity deserve a special structure: a constant Leontief technology is assumed, to avoid, for instance, to produce refined petroleum from gas and electricity.

Figure 2 shows the nesting of the CES and Leontief functions used to represent the production function of industrial goods that are not considered as energy intensive and of services.

Figure 2: Structure of the production function for manufacture sectors and services in MIRAGE-POWER



Improvement in energy productivity is embedded, at the level of the capital-energy bundle, its growth follows the growth rate of the energy efficiency projected by the MaGE model (see above, Section 1).

Endogenous technical progress is also present in the model. It is implicit, as producers can substitute capital for energy when they renew their capital stock, according to a nested CES production function. Given the depletion rate used in MIRAGE, this leaves the possibility of renewing 90% of the installed equipments at the 2040 horizon considered here. This mechanism, which mimics a technical progress induced by the increase in the carbon price, limits endogenously the increase in this latter price.

Carbon dioxyde emissions are proportional to the consumption of the energy goods corresponding to fossil energy (coal, oil, gas, refined petroleum), based on fixed parameters determined in the initial year. They arise from the intermediate consumption (use in manufacture production processes) as well as the final consumption (e.g. domestic heating fuel) of fossil fuels.

GHGs other than carbon dioxyde, namely nitrous oxyde, methane and fluorinated gases are considered as emitted during the production process. More precisely, these three GHGs are treated as production factors within the production functions. Their position in the production function, i.e. their relative substitutability with respect to other factors and intermediate consumptions, varies across sectors, following Hyman, Reilly, Babiker, De Masin & Jacoby (2003). Their substitution elasticity is taken from the literature.

The climate policy instrument present in our framework is a tax on GHG emissions, which is GHG-sector-region and time specific. It can be interpreted as the shadow price of the regulations aiming at curbing the emissions. This is how countries implement their unconditional commitments in the Paris Agreement. The level of the tax is calculated endogenously in order to respect the target imposed on the GHG emissions of each country: an upward pressure on the emissions increases the tax so as to respect the cap defined by the NDC, at each date.

As referred to above, there are two exceptions to this general framework. First, for the EU, a separate tax that mimics the cap-and-trade carbon market is calculated endogenously for industries participating in the EU ETS.[12] More specifically, in order to reach the target of -55% of economy-wide emissions by 2030 set in the EU new NDCs, we consider in our simulation one specific tax to the ETS, and one that applies to all other sectors and to final consumers. The cap imposed to the emissions of the sectors covered by the ETS is the one proposed by the EU Commission in July 2021, i.e. 61% in 2030 with respect to 2005. The level of the tax supported by sectors not covered by the ETS and by households is set to achieve the Fit for 55 target, conditional on the reductions undertaken in the ETS sectors. Finally, we represent the free allowances allocated to some sectors among those covered by the ETS. Over the period 2013-2020, 57% of the allowances on the ETS were auctioned, while the remaining 43% were freely allocated to sectors "deemed to be exposed to a significant risk of carbon

[12] The ETS market actually concerns the EU Member States and a few other countries. Norway (the ETS represents only a small part of the taxation of this country), Liechtenstein and Iceland. The United Kingdom left the ETS during the Brexit and now implements its own system to reach its commitments. It is treated the same was as the EU, but with a cap-and-trade market which is disconnected from the EU-ETS. Our modelling restrains the European ETS only to EU27 members. Norway, Liechtenstein and Iceland implement their commitments but in a parallel system, not connected to the EU ETS.

leakage".[13][14] Free allowances are phased out as CBAM is introduced over a 10-year period.

The second exception is China.[15] Consistent with the approach taken for the EU, there are two carbon prices in China, one for the cap-and-trade market and one for the rest of the economy. The NDC in terms of intensity is transformed into an absolute emissions cap for the Chinese economy, using the MaGE GDP projections as a benchmark. The effort is distributed between the industries subject to quotas and the rest of the economy in proportion to their emissions in 2021.

For all other countries we consider all the *unconditional* commitments, and disregard conditional ones, as reported in the National Determined Contribution interim registry of the United Nations Framework Convention on Climate Change (UNFCC) at the COP26.[16]

We translate all the considered commitments, whether formulated in absolute or in intensity terms or formulated with respect to a business as usual reference, in a relative reduction with respect to 2014, the base year in our simulations. We then apply this reduction linearly from 2014 to the horizon retained in NDCs. If this horizon occurs before 2040, which is the case for the majority of the commitments considered, we keep the commitment unchanged until 2040. Technically speaking, the commitments translate in a yearly cap on GHG emissions, imposed to each committed region of our regional aggregation, and the model then endogenously adjusts the level of a tax on GHGs to meet this target.[17] In other words, we consider here that excpet China, the EU and the UK, countries are actually free to choose the policy instruments they prefer: subsidies, regulations, tax credits, carbon taxation provided they reach their overall unconditional NDCs.

Unless otherwise specified, emission data are taken from the GTAP-E database and the satellite data on non-CO_2 emissions provided by GTAP.

3 Results

To be completed.

[13] Directive 2003/87/EC provides this general principle of free allowances to some specific sectors. Then, the Commission Decision 2014/746/EU determines the list of the sectors deemed as exposed to leakage for the period 2015 to 2019.

[14] Considering the aggregation retained in our simulation exercise, we consider that all sectors covered by the ETS but the power generation benefit from free allowances. This is represented in the model as these sectors paying a reduced carbon price, while the power generation sector fully pays for the GHGs it emits.

[15] Based on the *Carbon Pricing Dashboard* developed by the World Bank – see https://carbonpricingdashboard.worldbank.org/map_data#price – 16 additional countries had national carbon pricing systems in 2021: Argentina, Canada, Chile, Colombia, Iceland, Japan, Kazakhstan, Korea, Mexico, Montenegro, New Zealand, Norway, Singapore, South Africa, Switzerland and Ukraine. South Africa made conditional commitments, and as such is not considered in our simulations as implementing a carbon pricing scheme. The 15 remaining countries are treated without specifically modelling their national carbon pricing system by sake of simplicity.

[16] We represent the commitments as reported in the NDC register at the end of December 2021.

[17] By construction, the GHG cap is *always* reached in our setup, it is not possible to be more virtuous than planned in the NDCs. Unless differently specified, the carbon tax covers all the emissions, included those due to the burning of fossil fuels by final consumers, with the exception of the emissions caused by the transportation of international freight, which are excluded from the Paris agreement.

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A Appendix

A.1 The regional and sectoral aggregation

We report below the aggregation retained to move from the 147 regions and 65 sectors of the GTAP 10.1 MRIO database to the 27 regions and 23 sectors of our simulations.

Table A1: Regional aggregation

MIRAGE	Aggreg. code	GTAP region
Argentina	Argentina	ARG
Asia (NDC BAU)	AsiaBAUA	BGD, IDN, LKA, MNG, THA, VNM
Asia (NDC Intensity)	AsiaInt	MYS, SGP
Australia	Australia	AUS
Canada	Canada	CAN
Chile	Chile	CHL
China	China	CHN
Colombia and Mexico (NDC BAU)	ColMex_BAU	COL, MEX
EFTA and UK (NDC Absolute)	EFTA_UK	CHE, GBR, NOR, XEF
European Union 27	EU27	AUT, BEL, BGR, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, GRC, HRV, HUN, IRL, ITA, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROU, SVK, SVN, SWE
India	India	IND
Japan (NDC Absolute)	Japan	JPN
Kazakhstan and Ukraine (NDC Absolute)	KazUkr_Abs	KAZ, UKR
Latin America (NDC Absolute)	LACAbs	BRA, CRI, GTM
Latin America (NDC BAU)	LACBAUA	ECU, JAM, PER, PRY
Middle East and North Africa (NDC BAU)	MENABAUA	GEO, IRN, JOR, KGZ, MAR, ARE, KWT, LBN, OMN, QAT
NewZealand (NDC Absolute)	NewZealand	NZL
Others (NDC Absolute)	OthAbs	AZE, ISR, TUN
Rest of America	OthAm	BOL, DOM, HND, NIC, PAN, PRI, SLV, TTO, URY, VEN, XCA, XCB, XNA, XSM
Rest of Asia and Oceania	OthAsiaOce	BRN, HKG, KHM, LAO, NPL, PAK, PHL, TWN, XEA, XOC, XSA, XSE, XTW
Rest of Europe	OthEur	ALB, XER, SRB
Rest of Europe (NDC Absolute)	OthEurAbs	RUS, BLR, XEE
Rest of MENA	OthMENA	ARM, BHR, EGY, IRQ, PSE, SAU, SYR, TJK, TUR, XNF, XSU, XWS
Rest of SubSaharan Africa	OthSSA	BWA, CIV, MDG, MOZ, SDN, TZA, XAC, XCF, XEC, XSC, XWF, ZAF, ZMB, ZWE, GHA
South Korea	Korea	KOR
SubSaharan Africa (NDC BAU)	SSABAUA	CMR, ETH, GIN, KEN, MUS, MWI, RWA, TGO, BEN, BFA, NAM, NGA, SEN, UGA
United States	USA	USA

Notes: Countries in bold characters in the first column conform their emissions to their NDCs; specific treatment for China detailed in the text. The *Aggregation code* column reports the short names used during the simulations. These names may be used in some figures and tables of the paper.

Table A2: Sectoral aggregation

MIRAGE	Aggreg. code	GTAP sector
Air transp.	AirTransp	atp
Beverages and tobacco	BevTob	b_t
Cattle and other animal productions	AnimProd	ctl, oap, rmk, wol, fsh, cmt, omt, mil
Chemistry	**Chemistry**	**chm, bph**
Coal	Coal	coa
Crops	Crops	pdr, wht, gro, v_f, osd, c_b, pfb, ocr
Oil Electricity	**ElOil**	**OilP, OilBL**
Coal Electricity	**ElCoal**	**CoalBL**
Gas Electricity	**ElGas**	**GasBL, GasP**
Renewable Electricity	ElRen	WindBL, HydroBL, HydroP, SolarP, OtherBL
Nuclear Electricity	ElNuclear	NuclearB
Electricity transmission and distribution)	ElTND	TND
Electronics	Vehicles	mvh, otn
Forestry	Forestry	frs
Gas	Gas	gas, gdt
Metal products	**Metals**	**i_s, nfm, fmp**
Oil	Oil	oil
Oth. transp.	OthTransp	otp, whs
Other food products	OthFood	vol, pcr, sgr, ofd
Other manuf. − energy intensive	**OthEI**	**ppp, nmm**
Other manufactured products	OthManuf	lum, rpp, ome, omf
Other primary products	OthPrimary	oxt
Other services	OthServ	wtr, cns, afs, ros, osg, edu, hht, dwe
Refined oil	RefinedOil	p_c
Services to businesses	BusiServ	trd, cmn, ofi, ins, rsa, obs
Textile	Textile	tex, wap, lea
Vehicles	Electronic	ele, eeq
Water transp.	SeaTransp	wtp

Notes: The *Aggregation code* column reports the short names used during the simulations. These names may be used in some figures and tables of the paper. In the simulations, the ETS covers the sectors marked in bold. Taking the sectors in GTAP 10.1 as the basic blocks of our aggregation, the sectors covered by the ETS have been identified based on the list of sectors and activities reported in the Annex I of the Directive 2003/87/EC of the European Parliament and of the Council and in the Annex of the Commission Delegated Decision 2019/708. The Directive lists the activities covered by the ETS and the Decision supplements the Directive with the list of the sectors deemed at risk of carbon leakage.

A.2 Additional results