A Dynamic Path to a Low Carbon Economy *

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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.

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Introduction

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.[1] Then, taking 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 166 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 (**?**).

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 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. GHG

[1] 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."

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 a representation of the 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 U.S. Energy Information Administration (EIA). 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 in absence of climate policies?" 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 COP27. 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, the magnitude of carbon leakage, 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 puts 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 mimicking the functioning of the ETS market and imposing a certain budget of emission quotas auctioned or freely allocated to firms in the ETS perimeter. One that applies to all other sectors and to final consumers. The reduction 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 onward by sake of simplicity.

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 COP27 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.[2]

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.

Substituting the optimality condition for energy, E in Eq. 1, GDP is projected as:[3]

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

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

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

MaGE departs from research aimed at translating Shared Socioeconomic Pathways (SSP) into economic scenarios.[4]. 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.[5]

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 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

[4]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

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

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 EIA.[6]

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.[7]

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. Energy, which substitutes with capital, is made of electricity (power) and fossil fuels. Electricity generation relies on fossil fuels (coal, oil, and gas), nuclear or renewable energy.

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.

The regional electricity producer provides aggregate electricity for intermediate consumption and households. Electricity as such can also be traded - meaning that the utility can export or import electricity (indifferently coming from the different sources of generation). 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.

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

[7]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).

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

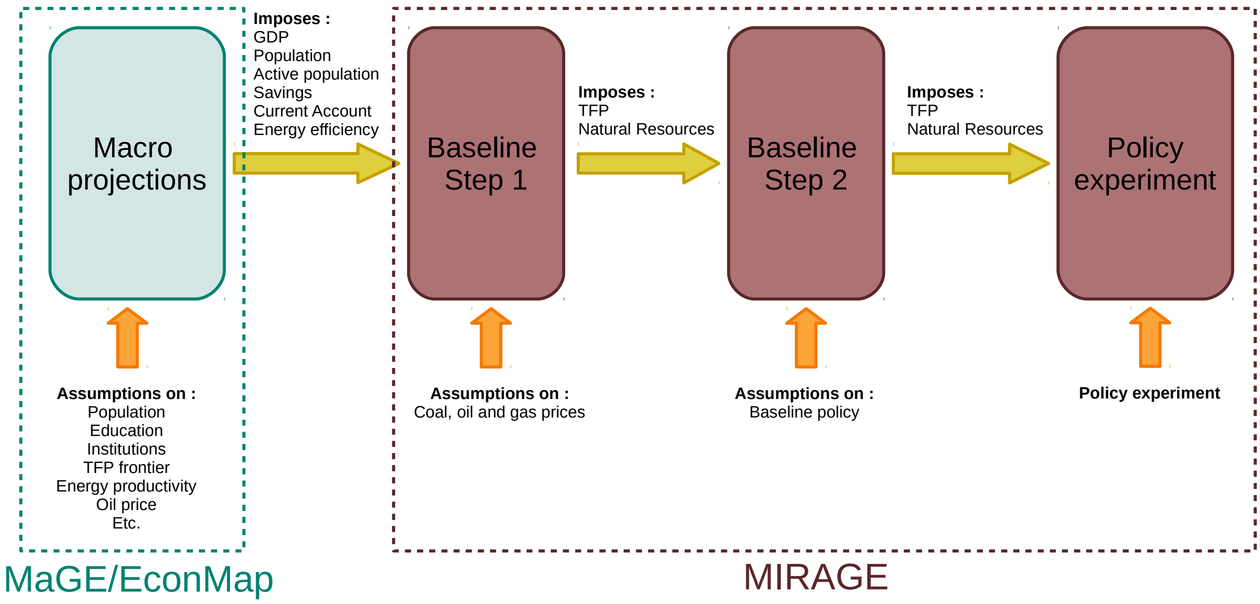
We build the BAU using the macroeconomic projections of the MaGE model (disseminated as the Econmap 3.1 database). A series of outputs of MaGE are imposed to MIRAGE-Power, while a series of exogenous variables are common to the two models. The exogenous variables common to the two models are: demography from the UN central scenario by cohort of five years and the oil price as projected by the EIA. The GE model also embarks the projected price of gas and coal (EIA projections) as exogenous variables in this first step. Reservation 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 exogenous 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. [8]

Noticeably, neither the Paris agreement nor the EU-ETS are present in this baseline.[9]

The third step is the policy experiment. In the non-cooperation scenario, 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 COP27). 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).[10] EU 27 and China deserves a special treatment in our third step, as far as their climate policies are concerned. In the cooperation scenario, for countries that submitted unconditional NDCs, they will mitigate their GHG emissions to meet their NDC unconditional targets.

Figure 1: The three steps in MIRAGE-Power



2.3 The GHG emissions

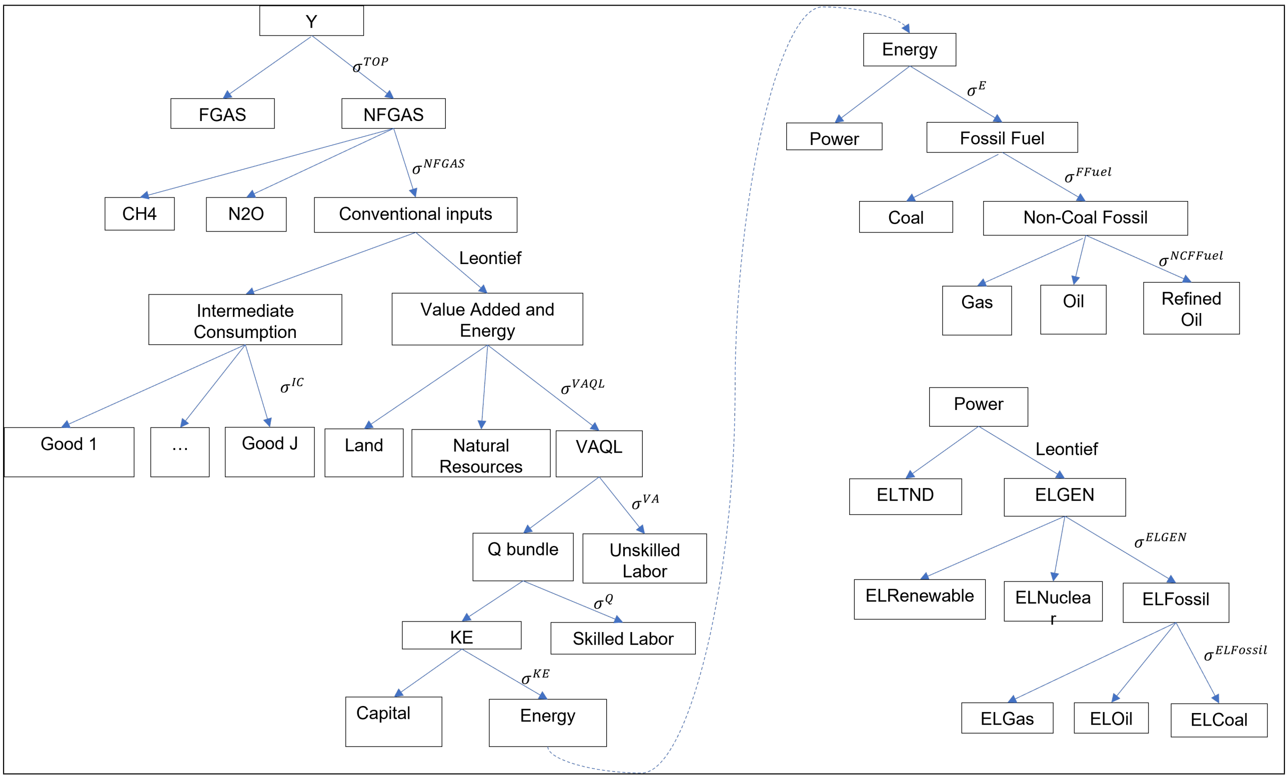
To account for GHGs emissions, MIRAGE-e explicitly considers the consumption of five energy goods (electricity, coal, oil, gas, refined petroleum). In firms' consumption, the bundle of these five goods substitutes with capital, in the value added structure, instead of substituting with intermediate con-

[8]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.

[9]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.

[10]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.

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



sumptions. 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.

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.

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 combination of policies (explicit taxes, command-and-control instruments) allowing to reach this abatement target. 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.[11] 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 explicit price of carbon 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 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 leakage".[12][13] Free allowances are phased out as CBAM is introduced over a 10-year period.

[11] 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.

[12] 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.

[13] 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.

The second exception is China in the non-cooperative climate policy scenario.[14] 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 COP27.[15]

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.[16] In other words, we consider here that except 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

3.1 A world with no climate policy

Our BAU is a world growing as projected by MaGE, meaning with demography, capital accumulation, technical progress, energy efficiency as above described, without engaging policies aiming to reduce

[14]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.

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

[16]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.

GHG emissions. Greenhouse gas emissions will increase due to the overall growth of the world economy, and the increasing share of the least energy efficient economies in world GDP. They will decrease due to the substitution of capital (with embodied technical progress) for energy as the price of oil rises, and the structural transformation of the most advanced economies away from brown goods.

The net macroeconomic outcome of these different forces is shown in Table 1 comparing the world economy in 2014 (our starting point) and 2040. Each block of columns is giving the share of each country or region in the total of the World economy in 2014 and 2040 for respectively GDP, exports, imports and GHG emissions. Countries and regions are ranked by decreasing order of their GDP in 2014. The first two columns illustrate the expected and well-documented shift in the centre of gravity of the global economy towards Asia. In 2014, the United States accounted for 20.4% of global GDP, and China for 14.1%. By 2040, these relative positions are expected to be reversed, with China accounting for 28.3% and the United States 14.4%. India is to become the third economy by its size in 2040, with 8.3% of the World GDP, if we do not consider the EU as one entity. A similar development leads to a decline in the EU27's share of world GDP from 20.2% to 11.5%. As a consequence of gravity forces driving international trade, the EU will see its share in world trade declining from 29% to 19% over the period considered.

The most interesting part of this exercise is to examine the trajectory of the global economy *beyond GDP*, looking in particular at emissions, the focus of our study. Comparing the shares in global GDP and global emissions highlights the initial difference in emissions intensity between the three main players: the US contributes 20.4% of global GDP in 2014 but only 14.7% of emissions. The difference is even more striking for the EU (20.2% and 8.9% respectively). In contrast, China's share of global emissions is much larger than its share of GDP in 2014 and is expected to remain so in 2040, despite an improvement. The same applies to India.

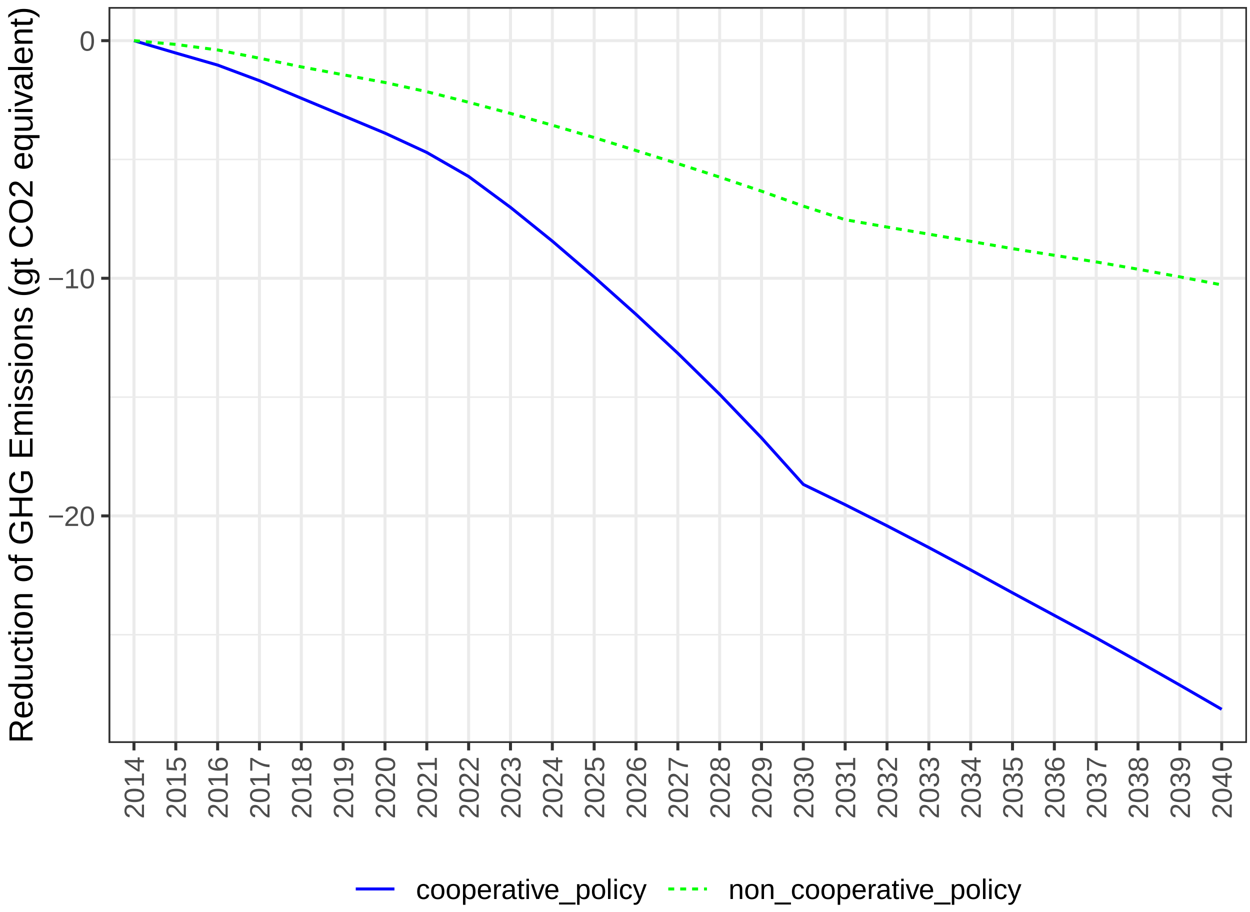
Figure 3 shows how world emissions can be reduced compared to the situation without a climate policy with different cooperation between the countries. The environmental consequence of such a reorientation of the world economy towards the least energy-efficient large economies, together with the steady growth of other countries due to demography, capital accumulation and technical progress, is the non-sustainable increase in GHG emissions. This conclusion, consistent with the repeated alarming reports of the IPCC, points to the necessity of determined action to mitigate GHG emissions.

Table 1: Share of each region on World totals

Region	GDP		Exports		Imports		Emissions	
	2014	2040	2014	2040	2014	2040	2014	2040
United States	20.4	14.4	9.4	7.4	12.1	11.8	14.7	10.8
European Union 27	20.2	11.5	29.6	19.6	29.1	19.4	8.9	5.0
China	14.1	28.3	12.0	18.8	9.9	14.4	23.3	30.4
Japan (NDC Absolute)	5.7	3.2	4.2	3.1	4.3	2.9	2.6	1.3
UK and EFTA (NDC Absolute)	5.3	3.6	5.8	4.2	6.1	5.0	1.7	1.0
Rest of MENA	3.4	3.7	4.1	3.5	3.8	4.6	5.1	4.5
Latin America (NDC Absolute)	3.2	1.7	1.4	1.1	1.7	1.8	2.7	1.6
Rest of Europe (NDC Absolute)	2.9	1.8	2.8	1.8	2.2	2.2	5.0	3.0
India	2.7	8.3	2.0	8.4	2.5	4.4	7.2	14.8
Colombia and Mexico (NDC BAU)	2.4	2.0	2.3	2.2	2.4	2.4	2.1	1.6
Asia (NDC BAU)	2.3	3.4	3.4	6.2	3.5	5.3	4.2	4.4
Canada	2.2	1.5	2.5	1.8	2.7	2.3	1.8	1.2
Rest of Asia and Oceania	2.2	3.7	3.8	6.5	3.7	5.7	3.0	3.9
Middle East and North Africa (NDC BAU)	2.0	1.8	3.1	2.6	2.7	3.7	3.4	3.3
South Korea	1.9	1.4	3.1	3.0	2.9	2.5	1.3	0.9
Australia	1.8	1.3	1.4	1.2	1.2	1.4	1.6	1.2
Rest of America	1.3	0.8	0.9	0.6	1.1	1.0	1.4	0.8
Rest of Sub-Saharan Africa	1.2	1.8	1.5	1.7	1.5	2.2	3.4	3.7
Sub-Saharan Africa (NDC BAU)	1.1	2.1	0.7	0.8	0.8	1.2	1.7	2.3
Asia (NDC Intensity)	0.9	0.9	2.7	2.9	2.6	2.8	0.9	0.8
Argentina	0.6	0.4	0.4	0.3	0.4	0.3	0.8	0.6
Others (NDC Absolute)	0.5	0.5	0.6	0.5	0.7	0.7	0.4	0.3
Latin America (NDC BAU)	0.5	0.5	0.4	0.4	0.5	0.4	0.5	0.4
Kazakhstan and Ukraine (NDC Absolute)	0.5	0.6	0.7	0.8	0.6	0.8	1.5	1.6
Chile	0.3	0.2	0.4	0.3	0.4	0.4	0.3	0.2
New-Zealand (NDC Absolute)	0.3	0.2	0.2	0.2	0.2	0.3	0.2	0.2
Rest of Europe	0.2	0.1	0.2	0.1	0.3	0.2	0.3	0.2

Notes: Countries are ranked by decreasing contribution to the World GDP in 2014.
Source: MIRAGE-Power, calculations by the authors.

Figure 3: Reduction of world emissions of GHG with climate policies



3.2 A world with a non-cooperative climate policy

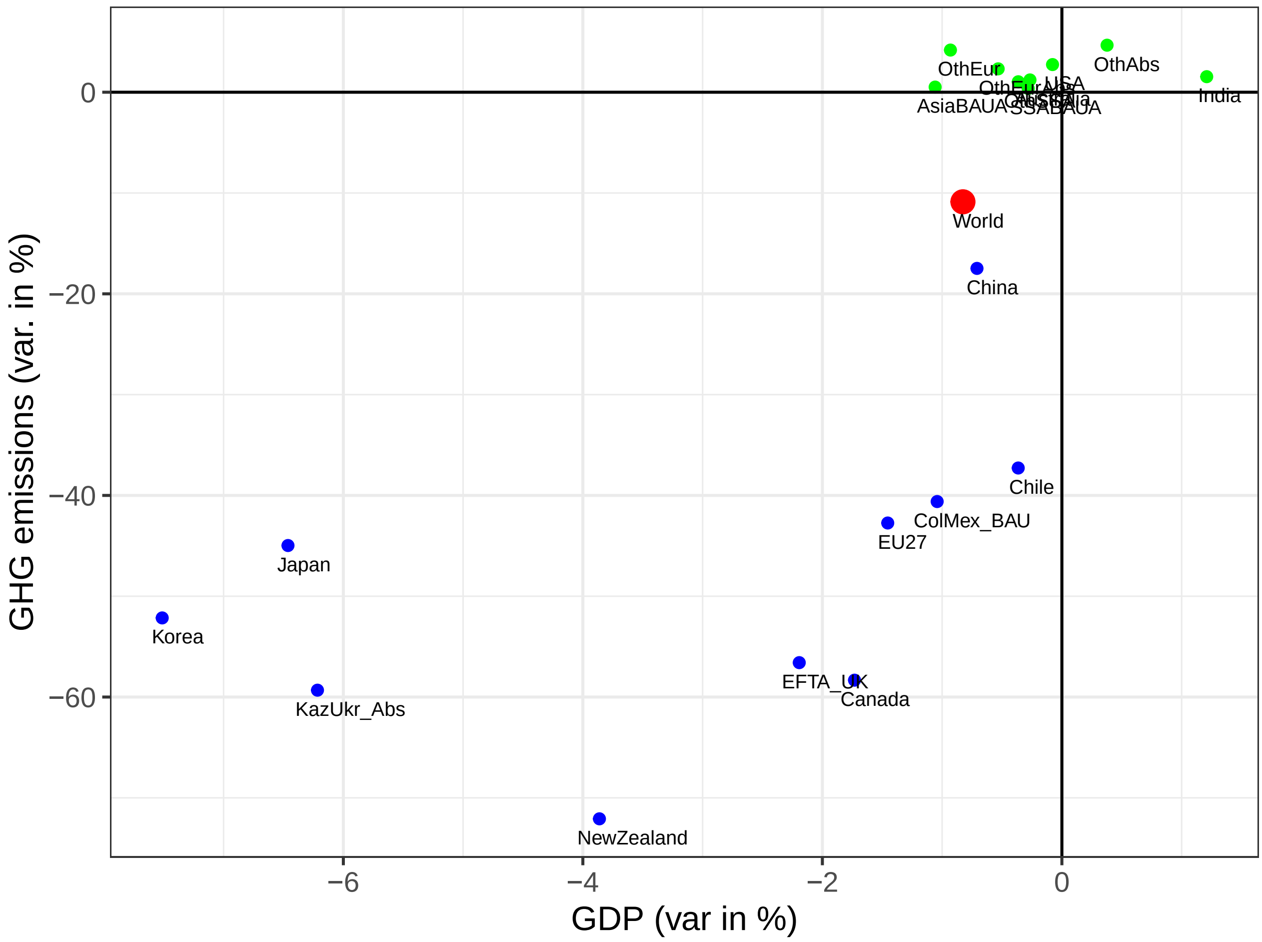
We now impose an endogenous price on GHG emissions under the assumptions described above: all countries *with a domestic carbon market in place by the end of 2021* are assumed to meet their NDCs, with the exception of China where the increase in carbon price and coverage is not sufficient. However, China is reducing its emissions in absolute terms, while at the same time increasing its economic size considerably over the period. Finally, the EU adopts the Fit for 55 package and thus reduces its emissions by 55% compared to 1990, introduces a CBAM and phases out free allowances.[17]

World GDP in this simulation is 0.82% below the BAU and World emissions are 10.9% below the BAU. The corresponding elasticity equal to 13.2 quantifies the cost of mitigating emissions at the 2040 horizon with a non-cooperative policy where not every participant fulfills its Paris commitments, provided that even achieving the Paris ambition would hardly put our planet on a trajectory compatible with the +1.5 degree Celsius target.

How the effort is shared among countries and regions is shown in Figure 4. The x axis shows the

[17] There are two carbon prices for the EU in the model: one is the price of emission quotas in ETS market, the other one is the implicit price of explicit carbon taxes and regulations in the rest of the EU economy.

Figure 4: Impact on GDP and GHG emissions: percentage change wrt the BAU in 2040 (non-cooperative climate policy)

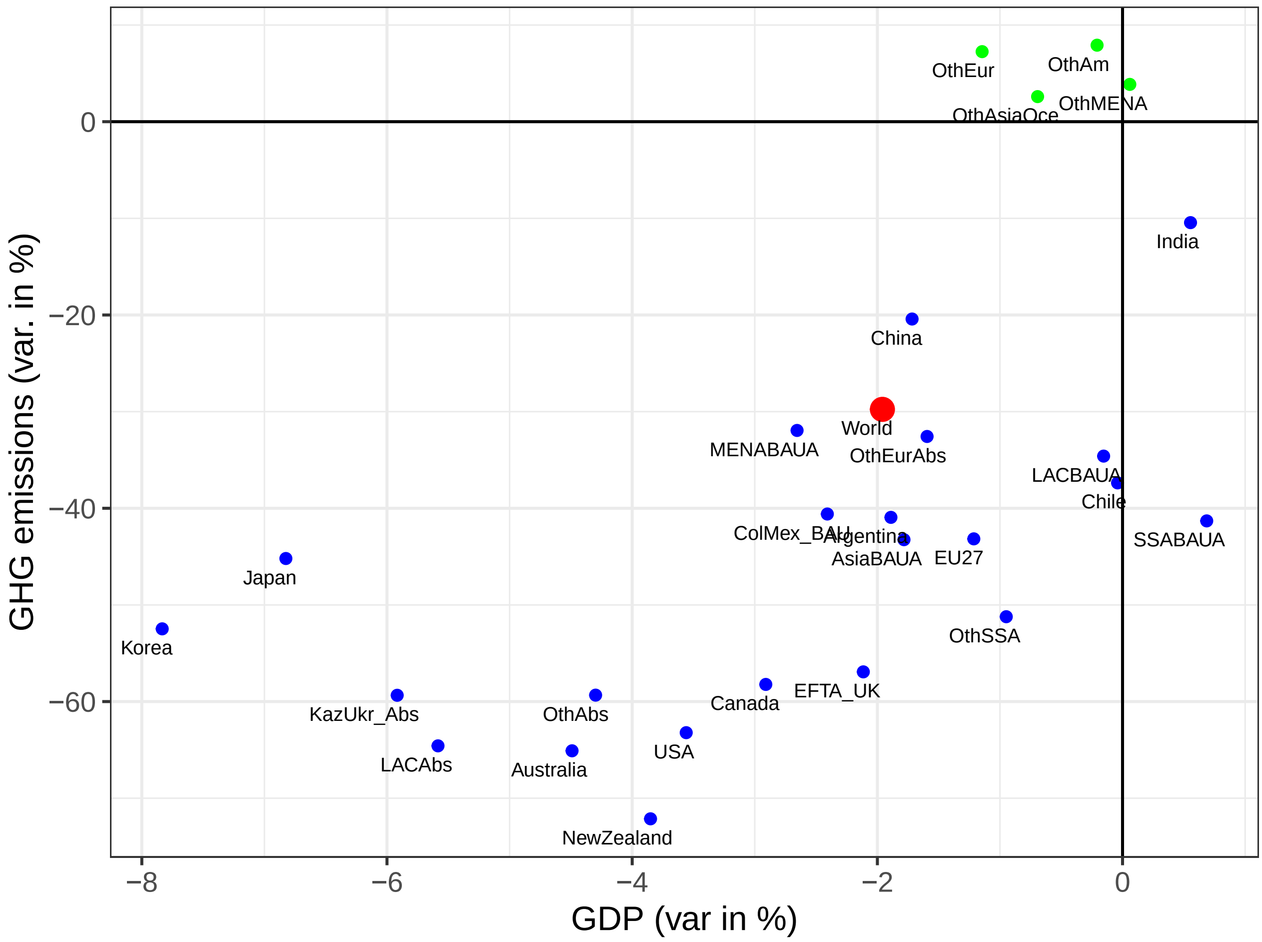


changes in the GDP wrt the baseline at the 2040 horizon for each country or region. The y axis does the same for emissions. The scatter plot delimits four quadrants corresponding to countries reducing their emissions at the cost of GDP losses (South-West), countries increasing their emissions while enduring GDP losses, and vice versa. We also plot the first diagonal. The figure is populated with two groups of countries and a couple of outliers.

The first group corresponds to countries bearing the cost of their participation to the preservation of climate. China is the first in the list by its economic size, if not by the reduction in emissions. New Zealand is the opposite example of a small country managing to dramatically curb its emissions, at a high cost. The EU is in an intermediate situation.

The second group of countries does not participate in the effort, although the economic benefits of non-participation are undermined by the reduced demand from participating countries. The most significant example of this result is the United States, which is penalised here by the extreme modelling choice of this section that only countries with a nation-wide carbon market will be able to meet their commitments. Indeed, the Inflation reduction Act will significantly curb US emissions, although it is

Figure 5: Impact on GDP and GHG emissions: percentage change wrt the BAU in 2040 (cooperative climate policy)



not based on a market instrument.

Lastly, the main outlier is India. This country benefits from the actions of other countries, mainly due to leakage, and increases its emissions in proportion to its GDP. An example of such benefit from leakage is the 8.6% increase in the Indian value added for Chemicals, contrasting with a -23.0% decrease in Korea and a 26% increase in Indian exports of chemical products to Korea.

3.3 A world with a cooperative climate policy

We now assume that once a country has committed to an unconditional NDC, it will meet its decarbonization targets. We impose a price on GHG emissions of these countries such that the NDCs will be reached. Compared to the previous scenario featuring a non-cooperative climate policy, the most significant changes are the participation of the largest emitters, including the U.S., China, India, and Australia. In other words, the United States or China will behave in exactly the same way as the European Union was supposed to in the previous section. Although a national carbon market has not been developed in the U.S., we still assume that it will reach the climate target, −50% absolute GHG emissions reduction compared to the 2005 level. Australia has enhanced the climate goals in 2022 by increasing the abatement target to 43% in 2030 compared to the 2005 level. The targets of China and India are in terms of carbon intensity, measured as GHG emissions per GDP. China commits to reducing 65% carbon intensity by 2030 compared to the level in 2005 and India commits to reducing 45% carbon *intensity* by 2030 compared to the level in 2005.[18]

Under this cooperative climate policy setup, world emissions are 29.8% below the BAU as more countries are participating in the efforts. The abatement is tripled compared to the simulation under a non-cooperative climate policy. World GDP is 1.96% lower than the BAU.

In the first group where countries bear an economic cost for participation in the preservation of climate, China and the U.S. are in the first places considering the GHG emissions reduction in absolute values. China's intensity goal is interpreted in the model as 20% emissions reduction compared to BAU. New Zealand is still the positive example that curbs its emission most. However, Australia also appeared on the list to curb its emission significantly. EU is in an intermediate situation as in the non-cooperative simulation.

The countries with no national NDCs fall into the second group with an increase in emissions, but with a drop in GDP due to the reduction in demand from the participating countries.

Interestingly, India is still the outlier where its GDP grows compared to BAU despite its participation in global mitigation. Indeed, due to the fast GDP growth of India, the abatement target of India, measured in carbon intensity, will turn into a non-significant reduction target at around 10%, compared to BAU. Because of the relatively low efforts, India will still enjoy the carbon leakage from the action of other countries.

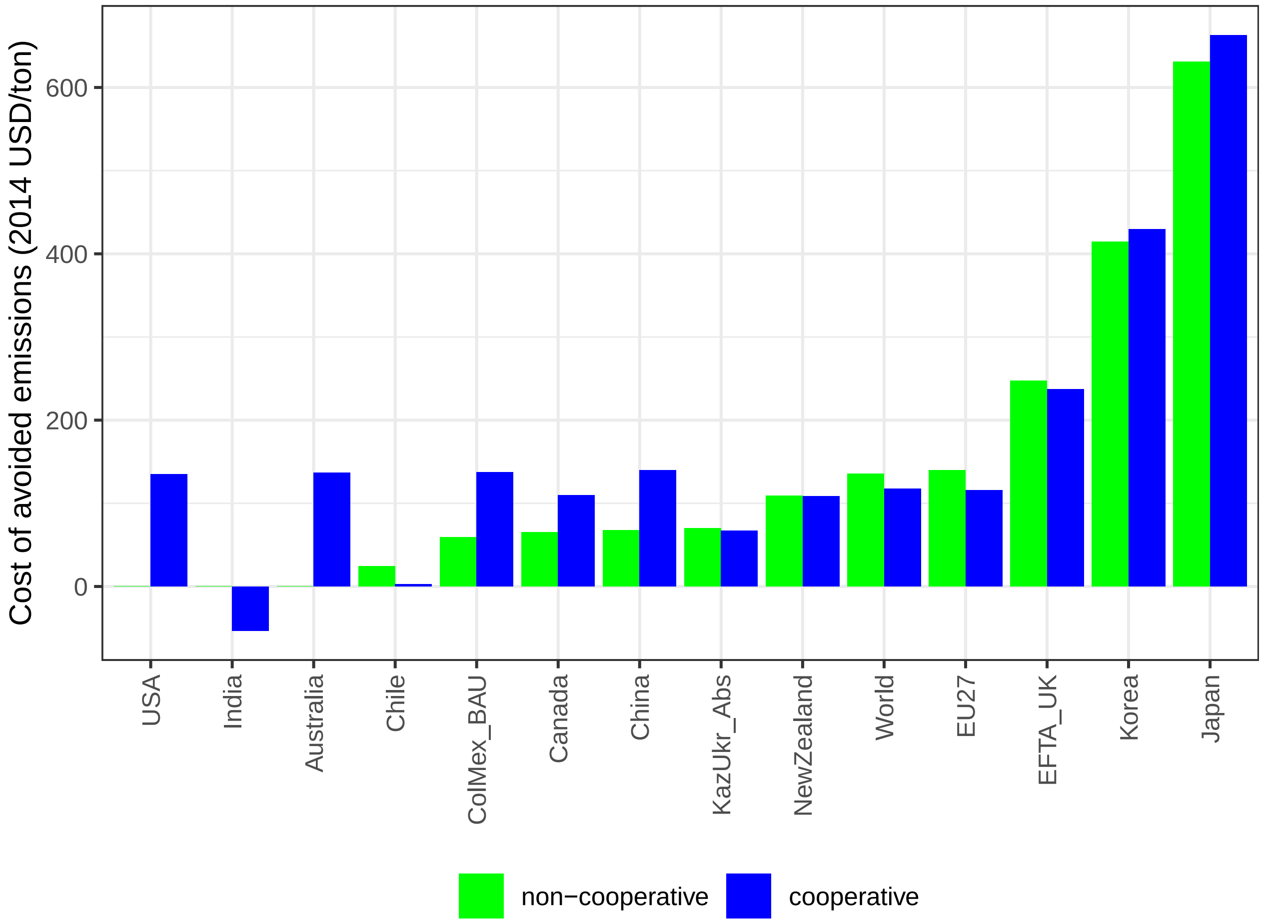
3.3.1 Abatement policy cost

We quantify and compare the abatement policy cost in figure 6, which is measured as GDP loss per ton of GHG avoided. In the cooperative scenario, while a higher level of abatement is reached globally, the policy cost of avoided GHG per ton for the world is lower than the cost under a non-cooperative climate policy. This is because more countries, especially the larger emitting countries, are sharing the abatement efforts.

The EU will benefit from the cooperative climate policy as the international demand for clean energy will increase significantly, and the EU will export more clean energy due to its comparative advantage in renewable energy. Furthermore, less carbon leakage is expected for the EU compared to

[18] This is a moderate commitment, as India will experience rapid growth over this period and will therefore ultimately only marginally reduce its absolute emissions, as we will show.

Figure 6: costs of avoided GHG per ton



the non-cooperative policy scenario. For example, there will be a slight increase in value-added for the energy-intensive sectors in the EU.

The cost of avoided GHG per ton for Korea and Japan remain high regardless of the world cooperation, mainly due to their energy structure at baseline being relatively more carbon-intensive. With carbon policies implemented, these two countries will face a decrease in value added in energy-intensive sectors, and an increase in exporting these products. Beyond Japan and Korea, the main emitting countries including the U.S., China, Canada, Australia, Columbia, and Mexico are facing an economic cost of GHG avoided per ton slightly higher or close to the world level, at around 120 USD/ton.

In line with the previous discussion, India remains an outlier with a negative cost. Indeed, although participating in the world climate cooperation, with less ambitious NDCs and fast-growing GDP, Indian will still benefit from the climate actions due to carbon leakage.

3.3.2 Energy transition

MIRAGE-Power allows for a transition between brown energy and green energy under the dynamic baseline, and under carbon pricing and regulations. First of all, the transition will mainly take place in the electricity sector, where the electricity generation techniques can adjust from fossil fuel based generation sources, to less GHG emitting techniques such as hydro, wind, solar, and nuclear. Second, industries will adjust their production techniques to become less emitting. This is realized by adjusting the energy structure by using less coal, oil, and gas, and using more electricity for production. In other words, industries, especially the energy-intensive industries, can realize GHG emissions reduction through two channels, either by reducing the production level, or by adopting a greener energy structure for production.

The different macroeconomic outcomes shown in the previous section are indeed driven by the strong adjustment at the sectoral level, and the sectoral level adjustment depends on the energy structure of the country. Figure 7 show the aggregate transition of the electricity generation techniques at the world level. Without any climate policy, the share of electricity generated from renewable energy will increase slightly from 19% to 24%, electricity generated from fossil fuels will decrease from 72.5% to 68.5%, and nuclear electricity share decreases from 8.5% to 7.5%. Under a non-cooperative climate policy, renewable electricity share will go up to 30%, and nuclear electricity share will go up to 9.2%. Cooperative climate policy will best promote the energy transition to green sources, with renewable electricity share increasing to 38%, and nuclear share increasing to 14.3%. At the global level, clean energy will represent more than 50% of electricity generation with a cooperative climate policy.

Figure 7: World electricity mix under cooperative & non-cooperative climate policy)

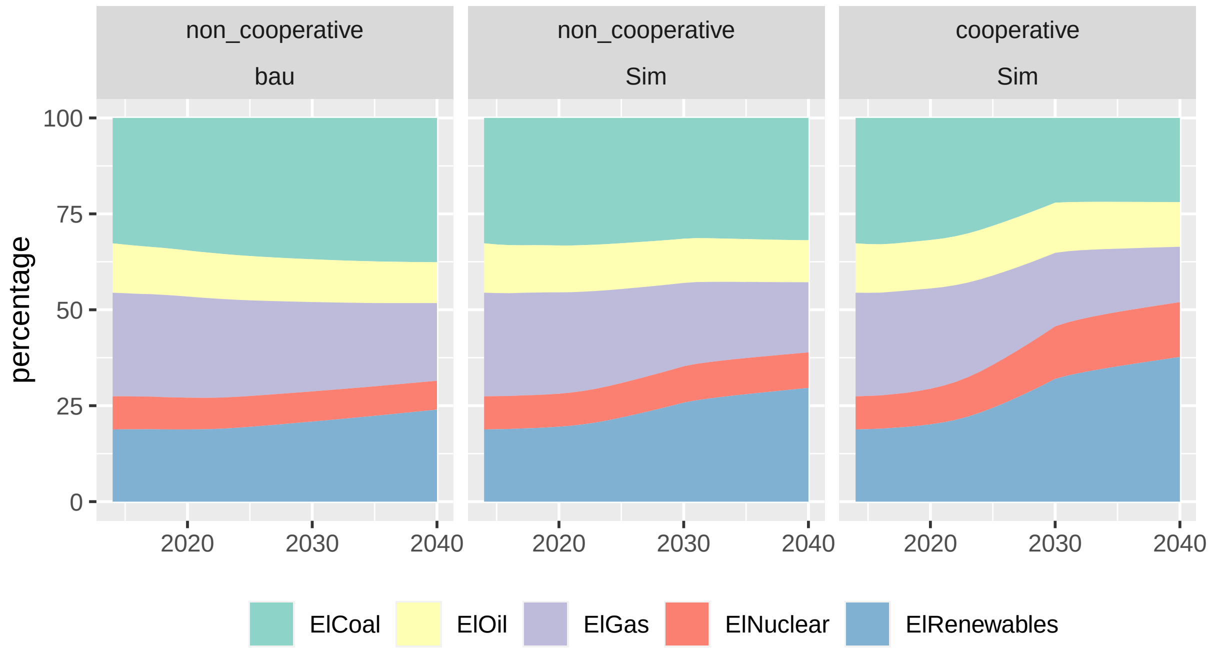


Figure 8: Electricity mix (cooperative climate policy)

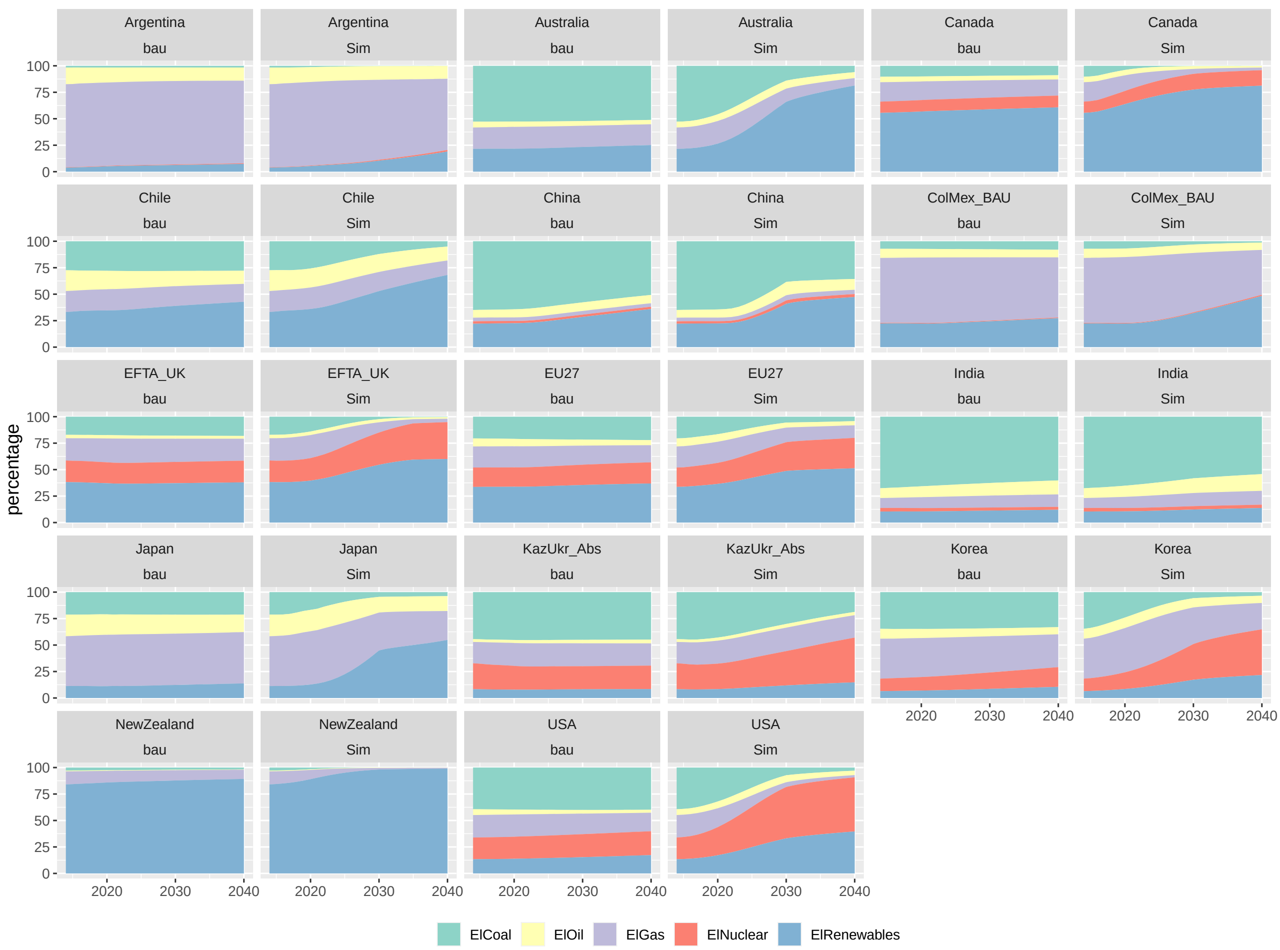
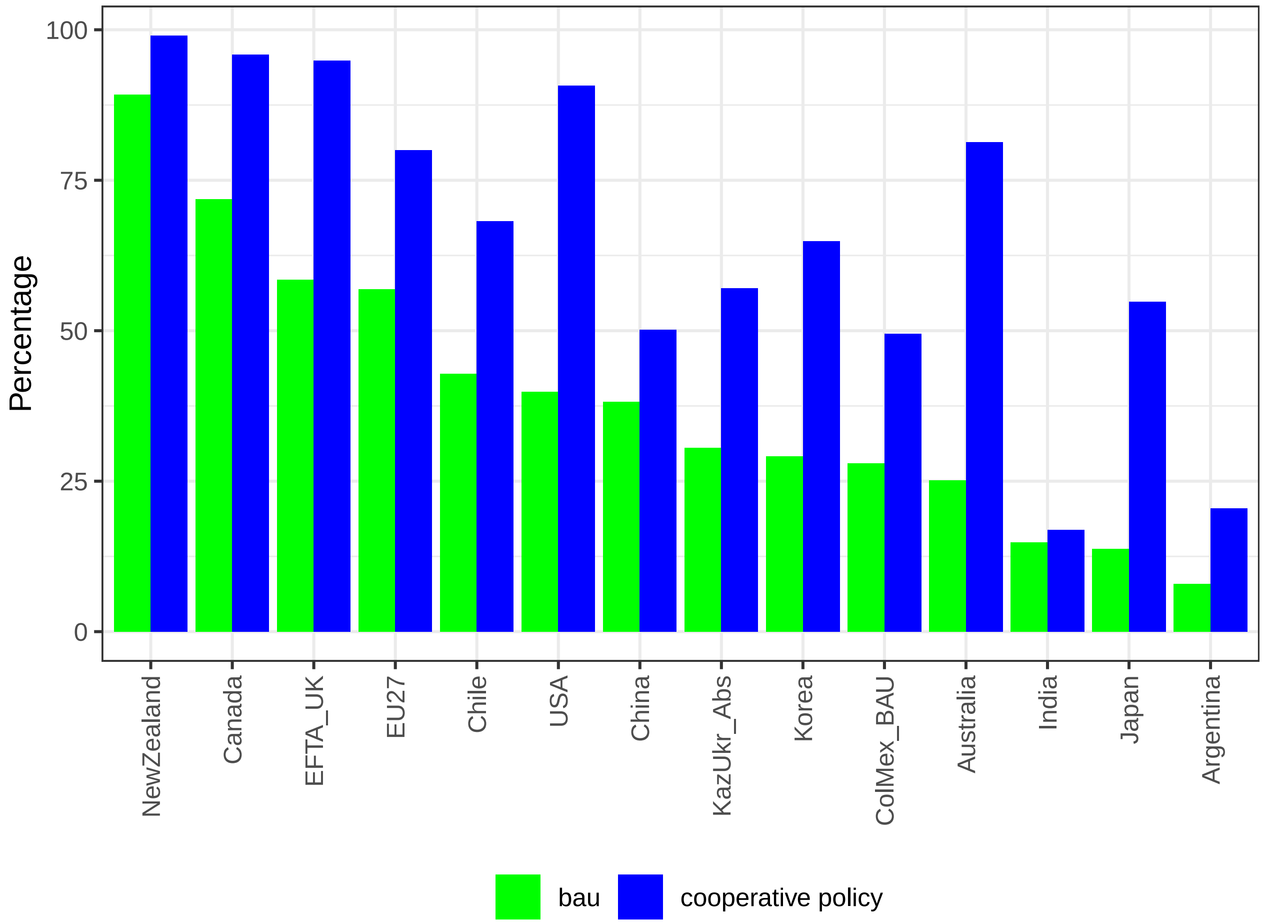


Figure 9: Clean energy share in 2045 (cooperative climate policy)



4 Conclusion

To be completed

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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

Figure A1: Impact on sectoral VA in the EU, percentage change wrt the BAU in 2040 (cooperative climate policy)

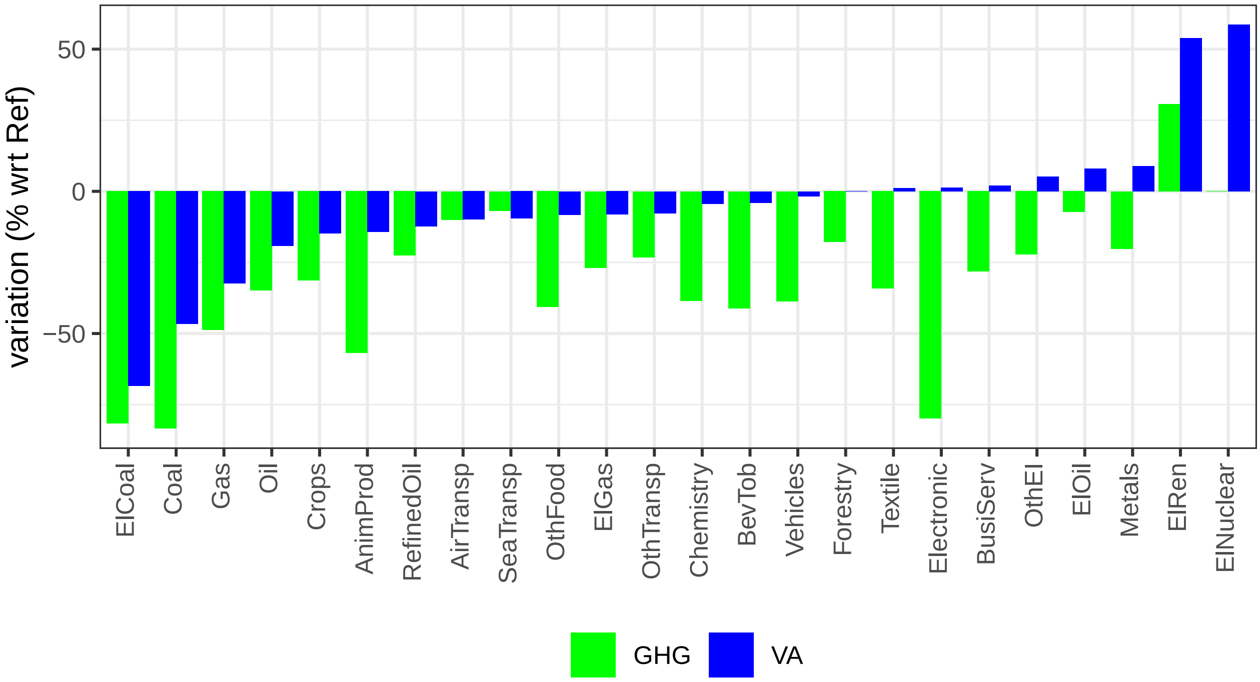

Figure A2: Impact on trade in the EU, percentage change wrt the BAU in 2040 (non-cooperative climate policy)

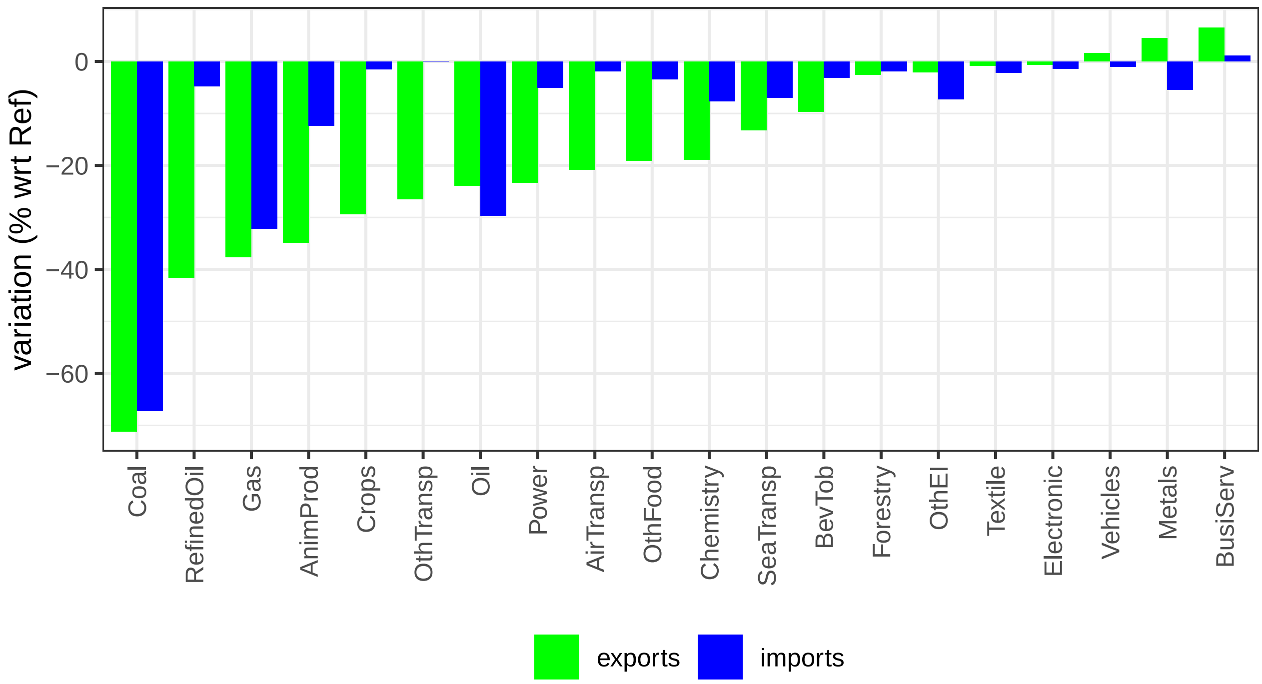

Figure A3: Impact on trade in the EU, percentage change wrt the BAU in 2040 (cooperative climate policy)