A Dynamic Path to a Low Carbon Economy

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Draft: May 30, 2022 – Do not quote

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Abstract

Achieving the climate objectives set out in the Paris Agreement requires a transition to low-carbon energy and, more generally, the structural transformation of our economies. We use the detailed long-term trajectory of the world economy on the basis of the macroeconomic projections of the MaGE 3.1 model featuring demography, education, life-cycle of savings, technological catch up, energy efficiency and current account of each country at the 2050 horizon. We integrate current account targets, investment and savings rates, labour force, skills and the GDP trajectories as exogeneous variables in a global and sectoral dynamic CGE model featuring imperfect competition, global value chains and GHG emissions. This business-as-usual trajectory of the world economy is then contrasted with a scenario imposing the Paris commitments as of the COP26, the EU having settled its cap-and-trade market while other countries actually engaged in mitigating their emissions also stick to their COP26 commitments. We show the level of the carbon taxation required to meet these targets, the demand and investment displacement towards the sectors that emit less, and the size and direction of leakages. For purely economic and short-sighted reasons, there is a huge incentive not to participate in the effort, which calls into question the cooperation logic of the Paris Agreement.

Key Words: Integrated Assessment Models, 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, 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 Global Value Chains (GVCs) and emissions of GHG (Bellora & Fouré 2019). To proceed, we use the MIRAGE-VA model. It is a global, dynamic, multi-sectoral and multi-regional model, featuring a detailed representation of energy use. Specifically, 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

[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."

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 value chains that, coupled to the results on emissions, allows to discuss in details the impacts on GHG leakage through international trade and on GHG footprints.

To build the business as usual (BAU) reference scenario in line with the macroeconomic projections, MIRAGE-VA 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 MRIO (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-VA enriches the information taken from MaGE with sectoral information (trajectories of each sector relative to the others within each economy), 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 their emissions meet their commitments under the Paris Agreement as of the COP26. This approach deserves to be substantiated. 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 nevertheless 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 only those countries that have a national carbon price in 2021 have proven their commitment and consider the most up-to-date version of the commitments made under the Paris Agreement, i.e. the updates to the NDCs made at COP26, which took place in November 2021.

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.

Lastly as far as the implementation of climate policies is concerned, the EU ETS put in place in 2005 deserves a special consideration. 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. 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. Our modelling integrates the phase out of free allowances on the ETS market as the carbon Border Adjustment Mechanism is progressively phased in over the 2026-35 period.

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 size of the demand and investment displacement towards the sectors that emit less, (iii) the change in the energy mix required to achieve the target emission reductions, (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-VA, 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:

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

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]

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

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

[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.

[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

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-VA). 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-VA.

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-VA 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-VA, 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.[6]

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

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

2 The General Equilibrium model

MIRAGE-VA (Bellora & Fouré 2019) 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 GVCs 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.

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.

Trade is represented with two different Armington structures, one for final consumption and one for trade in intermediates. This double structure explicitly accounts for GVCs. In both structures, domestic and imported goods are imperfectly substitutable, as are imported goods from different origins.[8] What the double Armington structure indeed captures is the difference in the preferences in the base year for a given sector (e.g. Vehicles) since, for instance, the share of imports coming from a given country is not the same whether they are of final (e.g. cars) or intermediate goods (e.g. components). Furthermore, it allows to apply policy shocks differentiated by the use of goods. Trade can be impacted by a wide range of measures, systematically differentiated according to the use of the affected goods. We explicitly consider tariffs and export taxes. Trade restrictiveness of non-tariff measures (NTMs), both on goods and on services, is also taken into account, under three possible different forms: tariff equivalents, export tax equivalents and iceberg costs. International

[7]MIRAGE stands for Modelling International Relationships in Applied General Equilibrium. MIRAGE-VA is the extension of MIRAGE-e documented in Fontagné, Fouré & Ramos (2013) that did not differentiate the demand of goods according to their use, whether for final or intermediate consumption, and that did not consider GHGs other than carbon dioxyde produced by burning fossil energies. More information on the version used here is available on the MIRAGE wiki: https://wiki.mirage-model.eu. The initial version of MIRAGE, which did not feature emissions of GHG, is documented in Decreux & Valin (2007).

[8]Elasticities of substitution across origins do not differ according to the use of goods, meaning that we actually assume that the behavior of an importer is the same whatever the kind of good (for final or intermediate use). These elasticities were structurally estimated by Fontagné, Guimbard & Orefice (2022). They are higher than the elasticity of substitution between domestic and foreign goods.

transportation is explicitly modelled: transportation demand is *ad volumen*, it can be satisfied through different transport modes, supplied by different countries.

Finally, MIRAGE-VA 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 MRIO database, that features a decomposition of trade in goods and services by final or intermediate use that is consistent with GTAP 10.1 standard database.[9] The 10.1 release of the GTAP database features 2014 as the last reference year. It represents the world economy considering 65 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-VA

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-VA, 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-VA 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-VA imports from MaGE, for each year and country, the GDP , the labour force (participation rate by gender $\times$ 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. Endogeneous TFP in MIRAGE-VA makes the two models consistent at

[9] Since the goods traded in the former versions of GTAP were aggregated within sectors over numerous HS-6 products categories, a given resulting sector provided the same category of good to final consumer and to other sectors that use it as an intermediate product. Combining COMTRADE and the Broad Economic Categories of the UN, GTAP MRIO fixes this problem: each bilateral flow in a GTAP sector is split into final and intermediate use. The outcome is a database of value of imports of commodities purchased by sectors (intermediate), households (final), government and investment (final), by source and destination country/region, at market, agent and world prices. Notice that although the database also provides the tariffs aggregated along the same dimensions, we do not rely on the latter as we proceed with our own aggregation of the MAcMap HS6 database. Since tariffs differ by HS6 category, with a simple combination with the BEC classification, followed by an aggregation at the GTAP sector level, for each GTAP sector we obtain tariffs differentiated by main use of the output of the sectors, as well as by the source and destination of the good.

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-VA, while keeping TFP and natural resources now exogeneous, at the levels set in the first step. Consequently, GDP, investment, energy prices are now endogenized. In this second step, we also represemt in a stylized way a sof Brexit, since it plays an important role in the decoupling of the UK climate policy from the one of the European Union. [10] Noticeably, neither the Paris agreement nor the ETS are present in this baseline.[11]

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).[12] EU 27 and China deserves a special treatment in our third step, as far as their climate policies are concerned. Details are provided in the following section.

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.

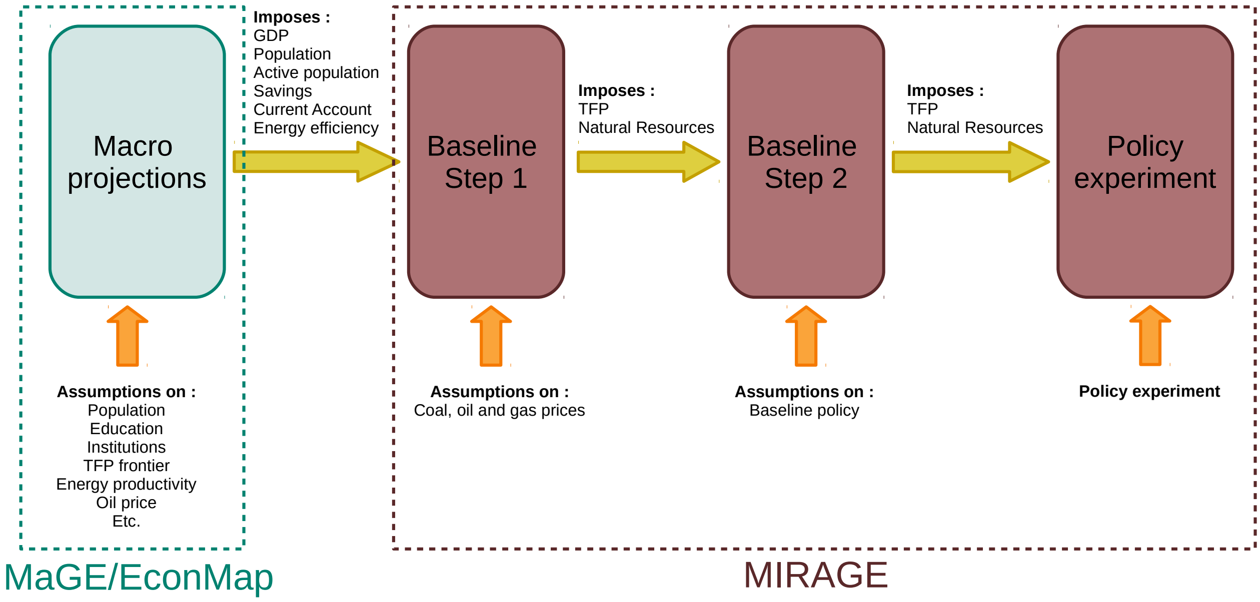
Improvement in energy productivity is embedded, at the level of the capital-energy bundle, its growth follows the growth rate of the energy efficiency projected by the MaGE model (see above,

[10] 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.

[11] 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.

[12] 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 1: The three steps in MIRAGE-VA



Section 1).

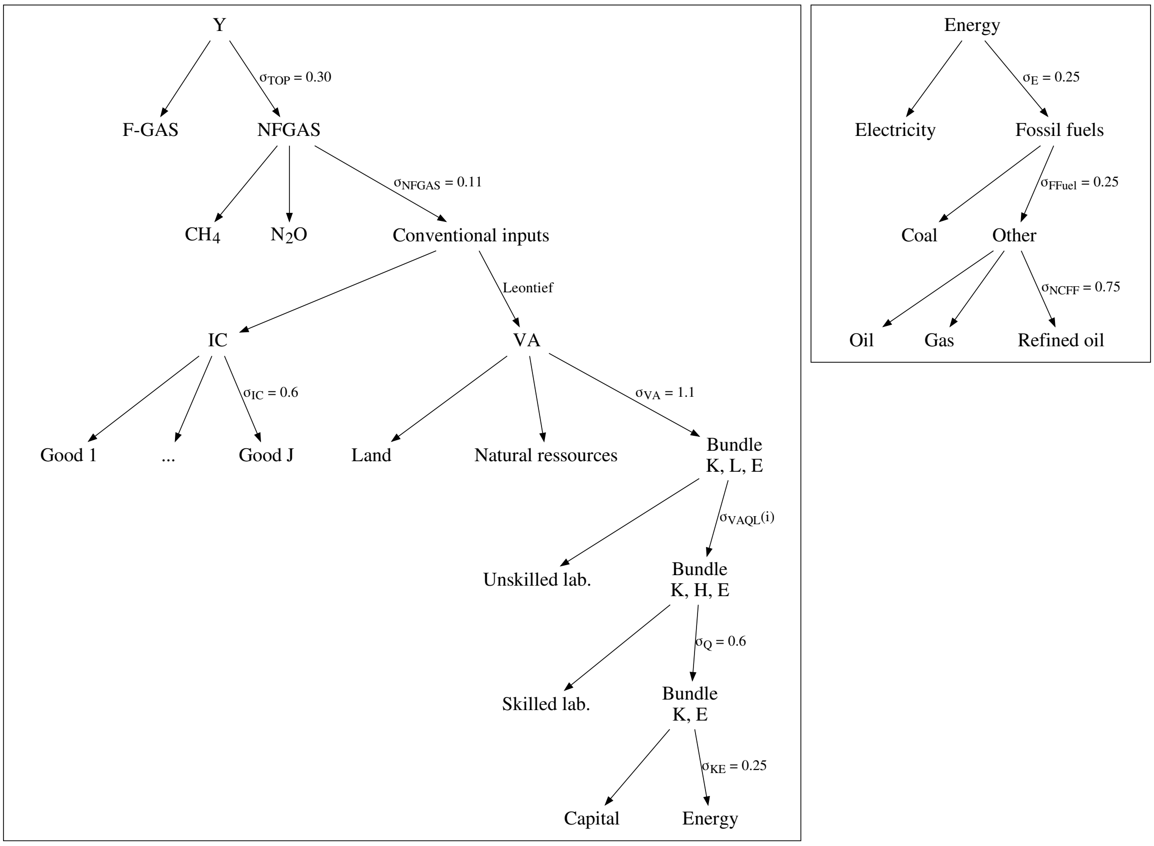
Endogenous technical progress is also present in the model. It is implicit, as producers can substitute capital for energy when they renew their capital stock, according to a nested CES production function. Given the depletion rate used in MIRAGE, this leaves the possibility of renewing 90% of the installed 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) (see details in Appendix **??**). 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

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



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.

Two exceptions to this general framework are worth mentioning. 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.[13] 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

[13]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. 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.

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".[14][15] Free allowances are phased out when CBAM is introduced in our scenario.

Second, the level of the tax is imposed exogenously in the case of China: it is determined by applying the rate of increase observed in the ETS market to the price of allowances in the Chinese carbon market at the end of 2021. China announced the implementation of its national carbon market two days after the presentation of the *Fit for 55* package by the European Commission. Such announcement made in July 2021 is a sign of good will, however counterbalanced by the low level of the carbon price recorded on the Chinese national market (on average, USD 7 per ton in 2021), which is not sufficient to reach the targets announced in the Chinese NDC – hence the specific treatment adopted for China.[16]

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.[17] We add here another important restriction, to stick to the spirit in which the European Commission conceived the CBAM, i.e. considering that its trading partners have developed climate policies which lack of ambition. We consider that only those countries that have already implemented, by the end of 2021, a *national* carbon market are going to fulfill the commitments they have taken in the Paris Agreement. We therefore assume that those countries that have not priced nationally the carbon they emit will not be able, or will not have the political willingness, to reach their target in terms of GHG emission reduction. Based on the *Carbon Pricing Dashboard* developed by the World Bank,[18] only 17 countries other than EU had national carbon pricing systems in 2021: Argentina, Canada, Chile, Colombia, Iceland, Japan, Kazakhstan, Korea, Mexico, Montenegro, New Zealand, Norway, Singapore, South Africa, Switzerland, United Kingdom and Ukraine.[19]

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

[14] 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.

[15] 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.

[16] This results in the reduction of China's GHG emissions by 15% in 2040.

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

[18] https://carbonpricingdashboard.worldbank.org/map_data#price

[19] South Africa made conditional commitments, and as such is not considered in our simulations as implementing a carbon pricing scheme.

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.[20] In other words, we consider here that countries fulfill their commitments based on a cap-and-trade system, while they are actually free to choose the policy instruments they prefer. As far as the CBAM is concerned, consistently with the European planned CBAM, only exporting countries that have introduced a national carbon market will be allowed to deduct this price from the compensation at the border. In other words, the implicit price of carbon regulations is not integrated in the calculation of border adjustment.

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

What are the environmental and economic consequences of the COP26 NDCs implemented by a limited number of participating countries, combined with the European Fit for 55 package? The answer is intuitive: the countries that are making the most significant efforts to reduce their greenhouse gas emissions will bear most of the cost of participating in the preservation of a global public good. They will also dramatically reshape the structure of their economies, reallocate resources and deplete capital. All of this should lead to a sharp reduction in their emissions, the objective of this policy, but at what may be a significant economic cost. On the other hand, countries that do not comply with their NDCs will benefit from carbon leakage, which will support their brown industries and increase their emissions, while suffering from reduced demand from more ambitious countries. The outcome of these two forces is an empirical question. We now put numbers to these mechanisms and show the diversity of economic and environmental outcomes for different countries and regions.

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

[20]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. China is not considered here, as we assume a time-varying exogenous carbon price rather than a fixed cap.

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 21.9% of global GDP, and China for 13.3%. By 2040, these relative positions are expected to be reversed, with China accounting for 26.7% and the United States 15.7%. 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 20.1% to 12.0%. As a consequence of gravity forces driving international trade, the EU will see its share in world trade declining from 30% to 20% 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 21.9% of global GDP in 2014 but only 14.8% of emissions. The difference is even more striking for the EU (20.1% 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.

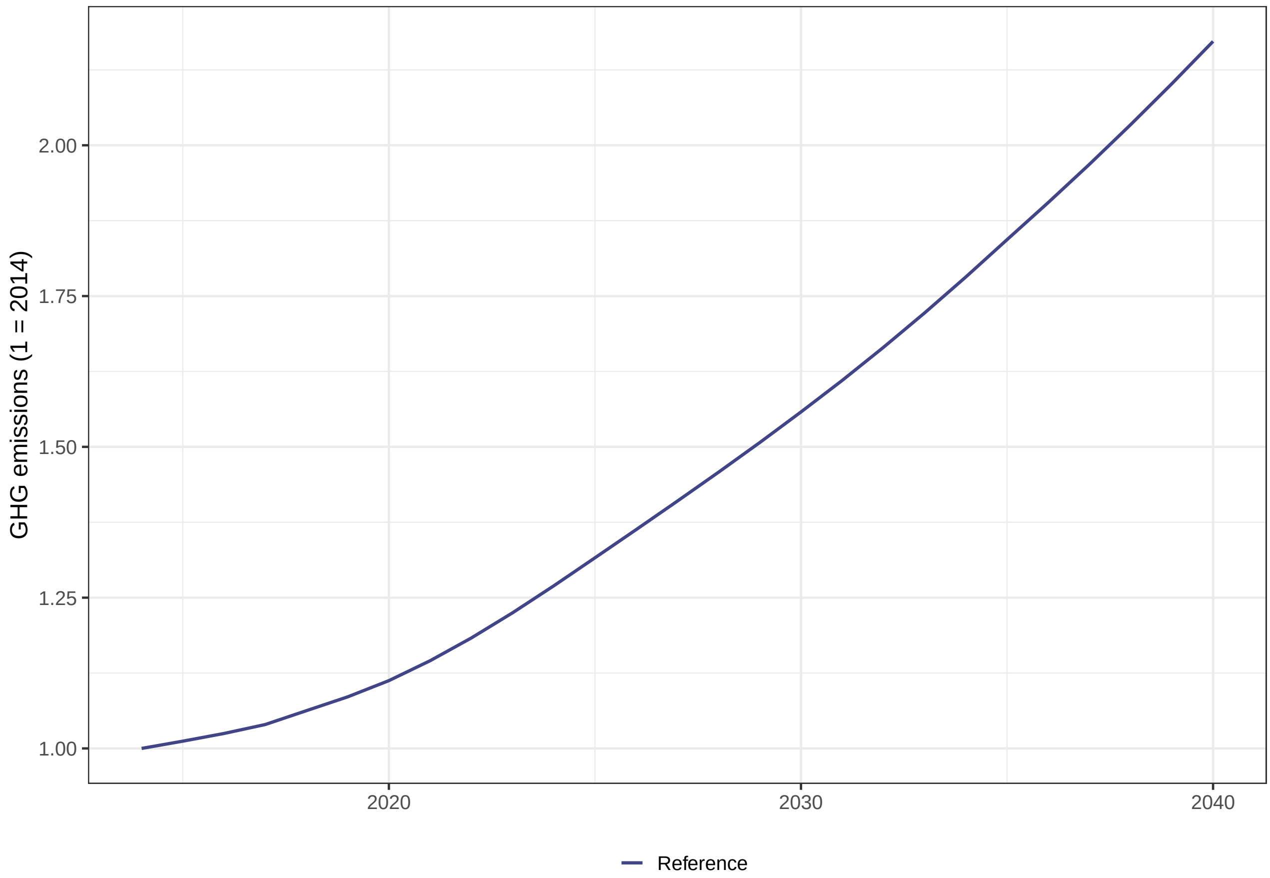
The environmental consequence of such a reorientation of the world economy towards the least energy-efficient large economies, together with the steady growth of other countries due to demography, capital accumulation and technical progress, is the non-sustainable increase in GHG emissions shown in the Figure 3. This conclusion, consistent with the repeated alarming reports of the IPCC, points to the necessity of determined action to mitigate GHG emissions. As the Paris Agreement was signed in 2015, we now have enough distance to assess its effects, bearing in mind that not all countries have committed themselves with the same determination to their NDCs. We will do so in the next section by assuming that the EU implements its Fit for 55 plan, while only those countries that had committed to carbon pricing at the national level in 2021 will manage to achieve their decarbonisation targets at the 2040 horizon.

Table 1: Share of each region on World totals

Region	GDP		Exports		Imports		Emissions	
	2014	2040	2014	2040	2014	2040	2014	2040
United States	21.9	15.7	9.5	7.8	12.0	11.7	14.8	10.5
European Union 27	20.1	12.0	30.1	21.2	29.4	20.3	8.9	4.8
China	13.3	26.7	12.0	17.2	9.7	14.2	23.3	31.4
Japan (NDC Absolute)	5.9	3.5	4.2	3.3	4.4	2.9	2.7	1.4
EFTA and UK (NDC Absolute)	5.4	3.9	5.9	4.8	6.3	5.5	1.7	1.0
Rest of MENA	3.3	3.8	4.1	3.6	3.8	4.5	5.2	4.2
Latin America (NDC Absolute)	3.2	1.8	1.4	1.0	1.6	1.6	2.7	1.7
Rest of Europe (NDC Absolute)	2.7	1.8	2.8	1.9	2.2	2.3	5.0	2.9
India	2.6	8.3	2.0	8.5	2.4	4.5	7.2	16.6
Asia (NDC BAU)	2.3	3.5	3.4	5.5	3.5	5.1	4.2	4.5
Canada	2.3	1.6	2.5	1.9	2.7	2.4	1.8	1.2
Colombia and Mexico (NDC BAU)	2.1	1.9	2.0	2.0	2.4	2.3	2.0	1.6
Rest of Asia and Oceania	2.1	3.1	3.7	5.6	3.7	5.2	3.0	3.2
Middle East and North Africa (NDC BAU)	1.9	1.5	3.1	2.4	2.7	3.3	3.4	2.7
Australia	1.8	1.4	1.4	1.2	1.2	1.4	1.6	1.2
South Korea	1.8	1.4	3.1	3.0	2.9	2.5	1.3	0.9
Rest of America	1.3	0.9	0.8	0.7	1.1	1.1	1.3	0.8
Rest of SubSaharan Africa	1.2	1.6	1.5	1.6	1.5	2.2	3.4	3.3
SubSaharan Africa (NDC BAU)	1.1	2.0	0.7	0.9	0.8	1.2	1.8	2.3
Asia (NDC Intensity)	0.9	0.9	2.7	3.0	2.6	2.9	0.9	0.8
Argentina	0.7	0.5	0.4	0.4	0.4	0.4	0.8	0.6
Kazakhstan and Ukraina (NDC Absolute)	0.5	0.4	0.7	0.7	0.6	0.6	1.5	1.1
Others (NDC Absolute)	0.5	0.5	0.6	0.5	0.7	0.7	0.4	0.3
Latin America (NDC BAU)	0.4	0.5	0.3	0.4	0.4	0.5	0.5	0.5
Chile	0.3	0.3	0.4	0.3	0.4	0.4	0.2	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	0.1

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

Figure 3: World emissions of GHG in the BAU



4 A world with a non-cooperative climate policy

We now impose a tax 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.

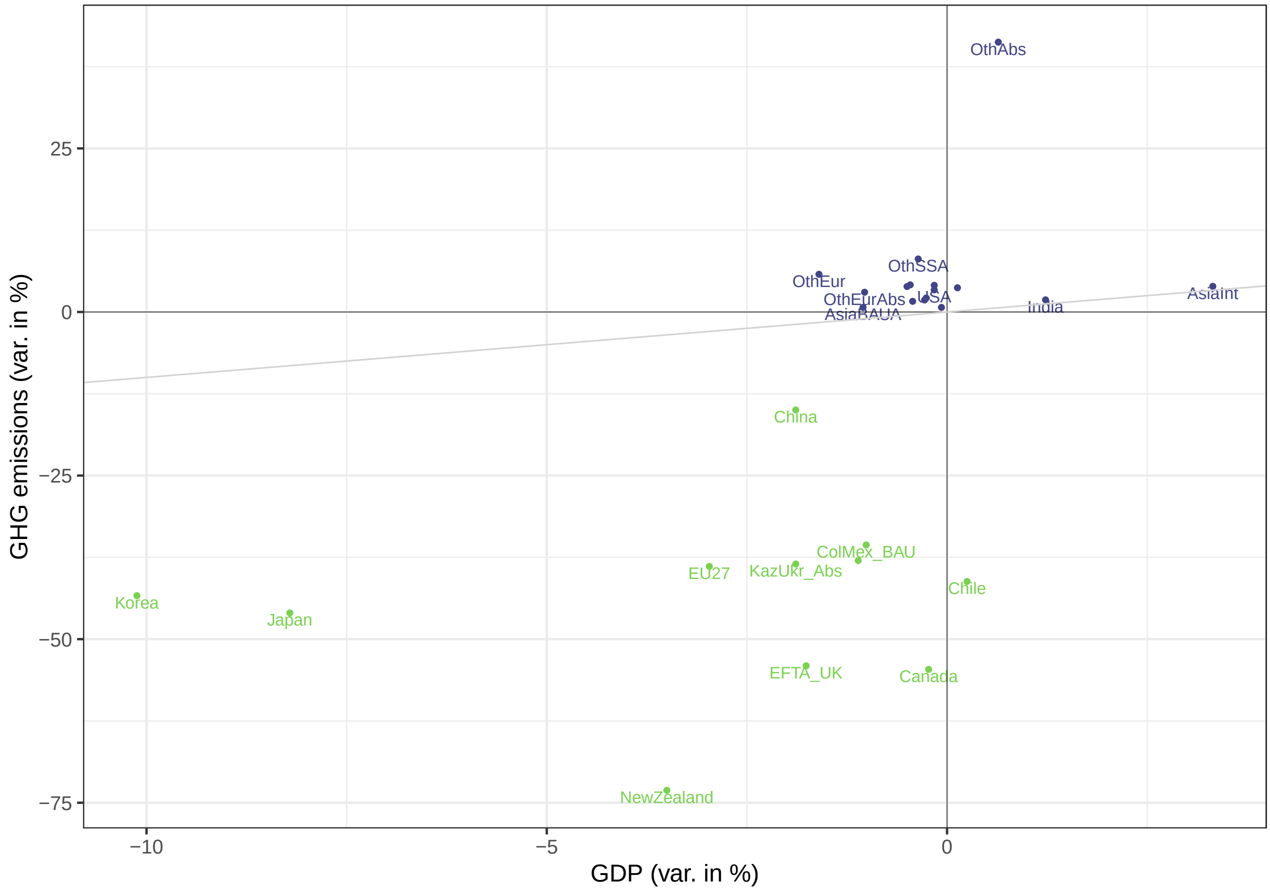
World GDP in this simulation is 1.4% below the BAU. World emissions are 8.6% below the BAU.[21] This elasticity equal to 6 quantifies the cost of mitigating emissions at the 2040 horizon with a semi-cooperative policy where not every participant fulfill its Paris commitments, provided that even achieving 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 changes in the GDP wrt the baseline at the 2040 horizon for each country or region. The y axis does

[21]See Figure A1 in Appendix A.2

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.

Figure 4: Impact on GDP and GHG emissions: percentage change wrt the BAU in 2040



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. The EU is in an intermediate situation.[22] Korea and Japan are reducing their emissions in the same proportion as the EU, but at a much higher economic cost.

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 our extreme modelling choice that only countries with a nation-wide carbon market will be able to meet their commitments.

[22] One can get a sense of the effort required for Europe by looking at the price of emission quotas on the ETS market from 2014 on, and of the cumulation of the carbon tax and shadow price of regulations on the rest of the EU economy. This is shown in Figure A2in the Appendix A.2. For ETS allowances, the price reaches 275 euros at the horizon of 2030 set by the Fit for 55 package.

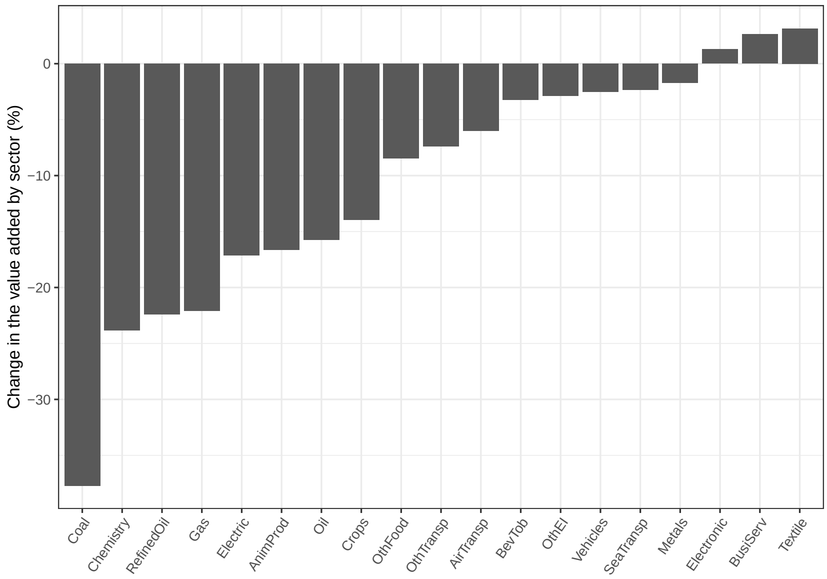
Lastly, the main outlier is India. This country benefits from the actions of other countries, mainly due to leakage, and increases its emissions in proportion to its GDP. An example of such benefit from leakage is the 12.9% increase in the Indian value added for Chemicals, contrasting with a -19.0% decrease in Korea and a 35% increase in Indian exports of chemical products to Korea.

Such different macroeconomic outcomes are driven by strong adjustments at the sectoral level. This is illustrated for the EU in Figure 5 for the EU and in Figure 6 for India. The contrast between the two figures, with the exception of the value added in call that declines in both countries, is striking.

However, this is only part of the adjustment that is taking place in participating and non-participating countries. Brown industries affected by carbon pricing or regulations are changing their production techniques to become less emitting. As shown in Figure 7 emissions (direct and indirect) of the brown sectors are reduced by far more than their value added, which indicates that the declining industries are also reducing their emission intensity. For example, the chemical industry reduces its value added by 25%, but its emissions by 55%. On the other hand, if we consider India in Figure 8, the 12.5% increase in the value added of the chemical sector is accompanied by the same increase in emissions from this sector. Thus, the gap in the emissions intensity of the chemical sector between the EU and India is widening as the EU implements its Fit for 55 package, which contributes to the leakage of this policy.[23]

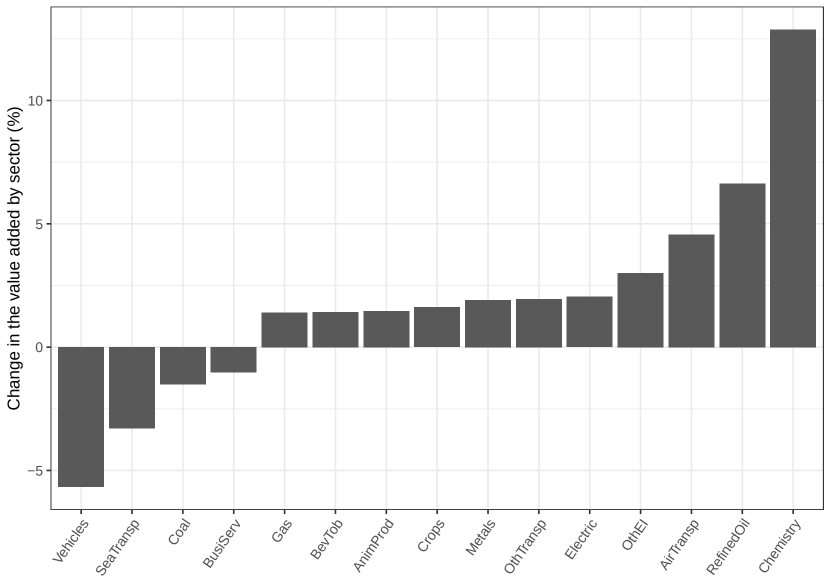
[23] Additional results for Japan and Australia are shown in Appendix A.2, respectively in Figures A3 and A4.

Figure 5: Impact on sectoral VA in the EU, percentage change wrt the BAU in 2040



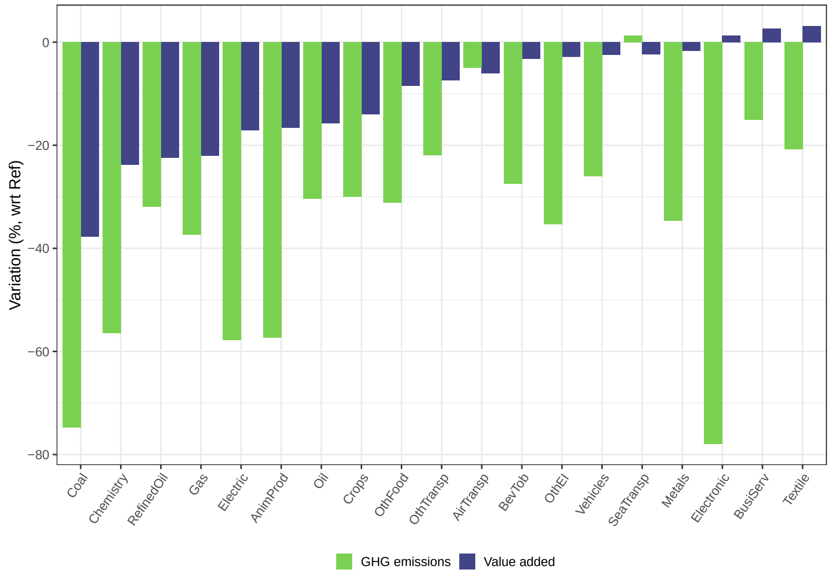
Note: Only changes above one percentage point are represented.

Figure 6: Impact on sectoral VA in India, percentage change wrt the BAU in 2040



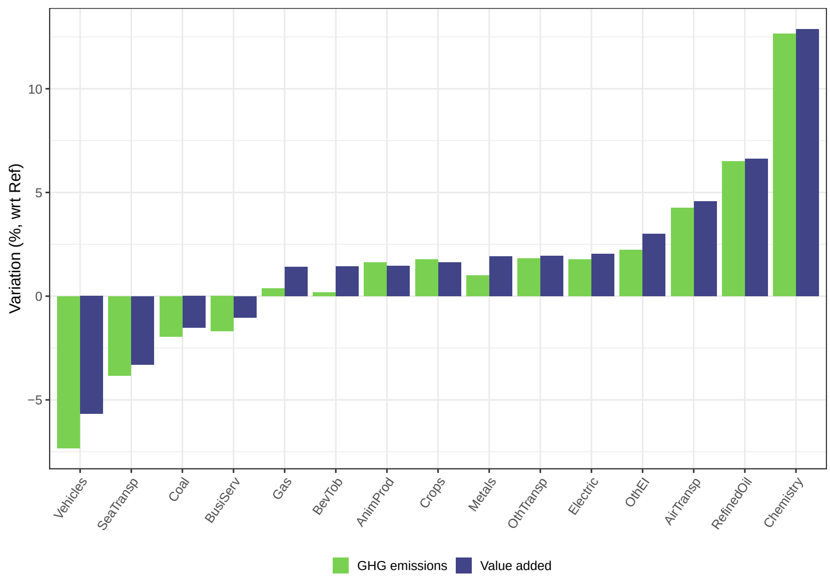
Note: Only changes above one percentage point are represented.

Figure 7: Impact on sectoral VA and emissions in the EU, percentage change wrt the BAU in 2040



Note: Only changes above one percentage point are represented.

Figure 8: Impact on sectoral VA and emissions in India, percentage change wrt the BAU in 2040



Note: Only changes above one percentage point are represented.

5 Conclusion

In order to quantitatively assess the economic and environmental consequences to be expected from a non-cooperative World after the Paris Agreement, we combine a macroeconomic growth model including labour, capital and energy with a global and sectoral dynamic general equilibrium model. Our (unsustainable) baseline scenario is driven by demographics, capital accumulation, technical progress and energy efficiency, in a BAU situation where the trends observed in the past are extended. Against this baseline, we quantify a scenario of incomplete implementation of the COP26 NDCs, combined with an implementation of the Fit for 55 package, including a gradual introduction of a CBAM and a phasing out of free allowances on the ETS.

The outcome in 2040 is clear. Firstly, the reduction in emissions is too limited at the global level to achieve the climate-friendly reduction target. This means that the participation of all countries in the effort is indispensable. Secondly, the countries involved in preserving this global public good bear a high cost in terms of GDP because of leakage. Finally, with few exceptions, non-participating countries hardly benefit from leakage because demand in participating countries collapses. But non-participating countries will not bear the cost of reducing their emissions either. This set of results characterises a well-known cooperation problem: each country engaged in reducing its emissions bears a significant economic cost, especially in brown industries, while its action does not reduce global emissions sufficiently to avert the gloomy climate outlook, due to lack of participation. This provides no incentive for other countries to participate.

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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
Electricity (incl. distribution)	**Electric**	**ely**
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: World emissions, BAU and scenario

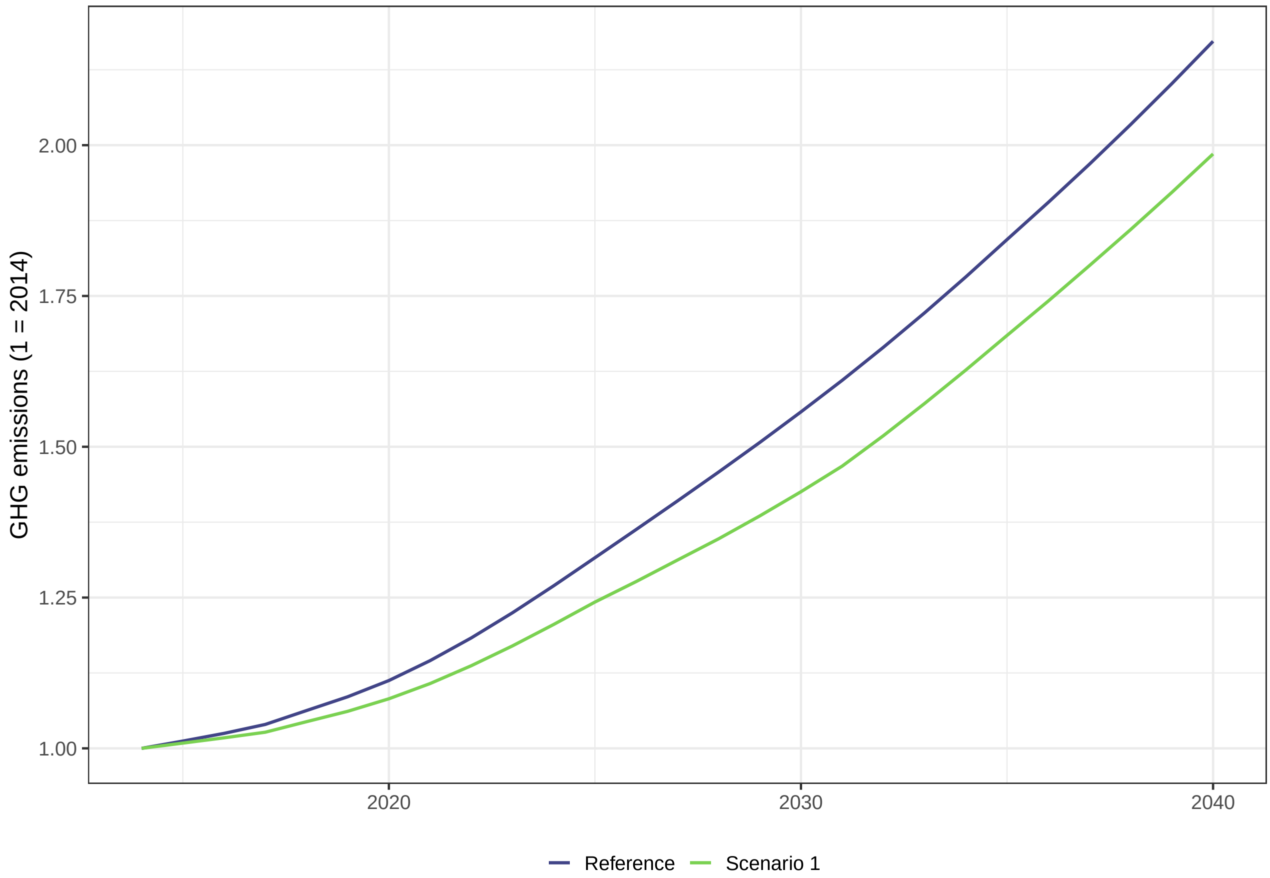

Figure A2: Evolution of the price of EU ETS allowances and of the carbon tax and shadow price of regulations within the rest of the EU economy

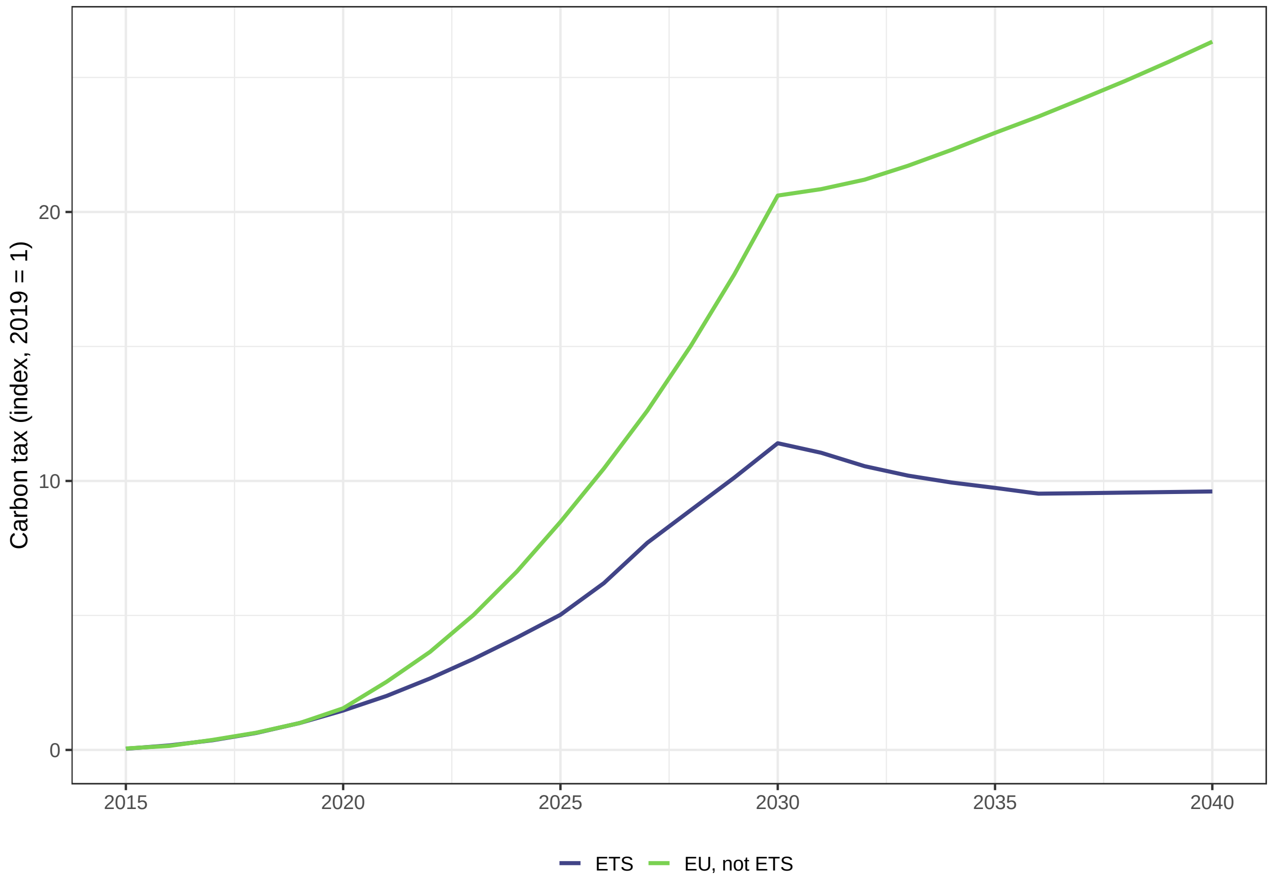

Figure A3: Impact on sectoral VA in Japan, percentage change wrt the BAU in 2040

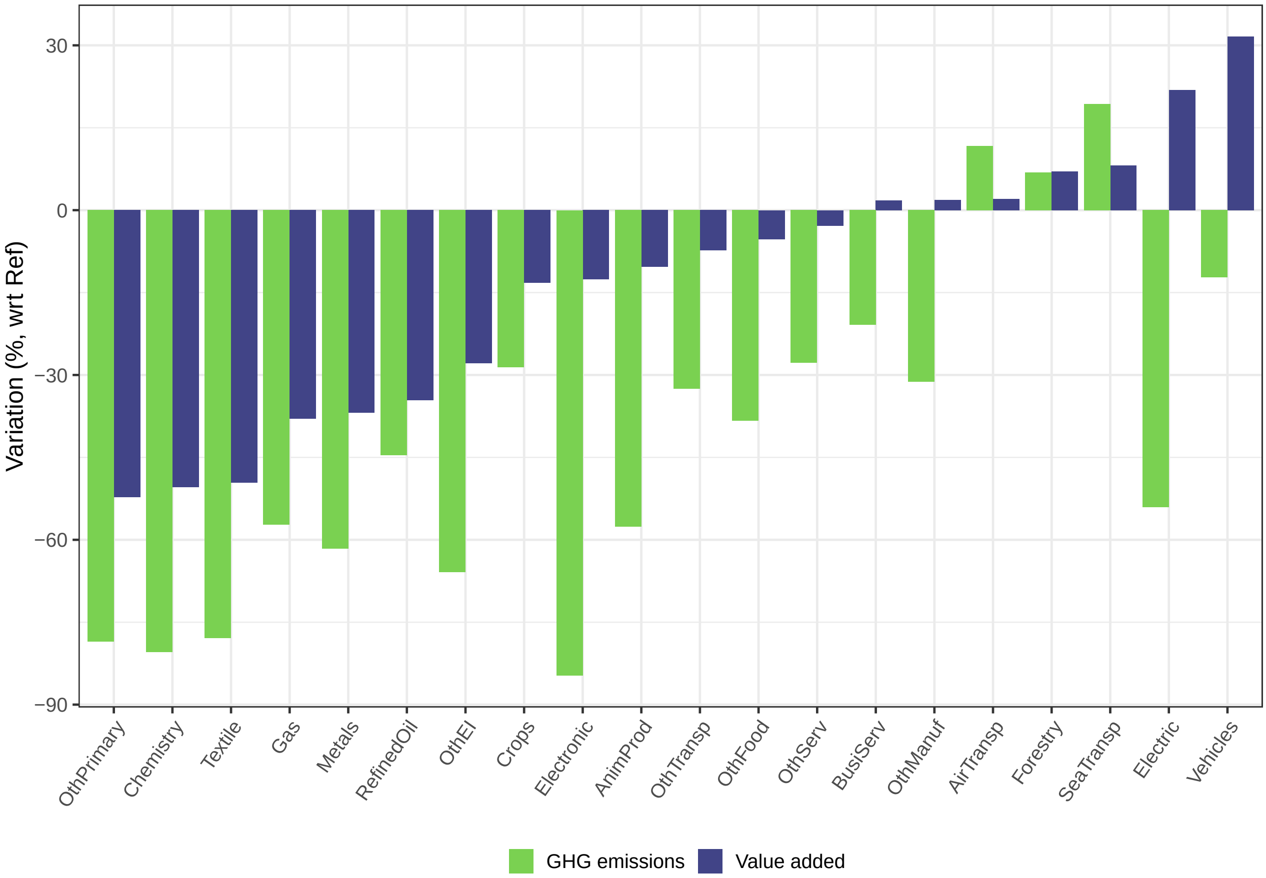

Figure A4: Impact on sectoral VA in Australia, percentage change wrt the BAU in 2040