Climate Mitigation Policies, Comparative Advantage in Trade and Restructuring of the Global Value Chains (GVCs)

Maksym Chepeliev, Maryla Maliszewska, and Wen Jin "Jean" Yuan

Abstract

This paper uses a combination of the TIMES Integrated Assessment model (TIAM-WORLD) and global computable general equilibrium (CGE) model ENVISAGE to analyze the impact of future climate mitigation policies. Simulation results indicate that on the macro level, the cost of putting the global economy on the low carbon transition pathways is manageable — stylized modeling suggests that even under the most ambitious climate mitigation scenario, a global GDP declines by only 1.4 percent in 2050 relative to baseline. Meanwhile, with increasing climate mitigation efforts, low carbon intensive sectors, such as electronics and transportation equipment, gain their share in global exports. The extent of such an expansion across countries is largely driven by the carbon revenue recycling approach, as well as carbon intensity of the corresponding production processes across countries. Finally, in terms of GVC participation metrics, our stylized modeling results indicate that while fossil fuels and energy intensive sectors experience a reduction in the GVC participation rates following an implementation of climate policies, service sectors and light manufacturing activities see a moderate increase in their involvement to the global values chains. These include such highly GVC-integrated commodities like computers and electronics and other light manufacturing goods. Thus, our analysis suggests that the climate mitigation policies stimulate higher integration into the GVCs of low carbon intensive commodities, while economies that specialize in such goods have better opportunities in navigating the low emission development transition.

1. Introduction and policy context

Humanity is facing a climate crisis (Ripple et al., 2020). In December 2015, countries that are Parties to the United Nations Framework Convention on Climate Change (UNFCCC) reached a landmark agreement, generally referred to as the Paris Agreement, to combat climate change. The main goal of the Agreement is to strengthen the global response to mitigate the effects of climate change by keeping a global temperature rise this century well below 2°C relative to pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C (UNFCCC, 2015). In order to reach this goal, a significant boost of the current policy efforts is needed (Rogelj et al., 2016; Sognnaes et al., 2021). Achievement of such an ambitious mitigation target would bring major co-benefits, including improved air quality (Markandya et al., 2018; Vandyck et al., 2018; Xie et al., 2018) and improved biodiversity (Albano et al., 2021; Urban, 2015). These co-benefits would come on top of the reduced climate-related damages, as well as lowered frequency and magnitude of catastrophic weather events (Ornes, 2018; Tol, 2018). At the same time, mitigation measures would also require a departure from the current developmental trajectory, implying drastic transformations for the energy system (Azevedo et al., 2021; Rogelj et al., 2015), changes in behavioral patterns (Marteau et al., 2021), such as dietary shifts toward less meat-oriented food systems (Clark et al., 2020; Theurl et al., 2020), as well as major infrastructural upgrades in many cases requiring an early retirement of the existing fossil fuel and energy-intensive capital assets (Tong et al., 2019).

Future climate mitigation policies would inevitably change the comparative advantages across countries and firms, benefiting cleaner and more sustainable activities, while leaving a major portion of the fossil fuel assets stranded (Mercure et al., 2018; Rempel and Gupta, 2021). To support this transition, new innovative commodities and technologies would appear, such as hydrogen (McPherson et al., 2018; Staffell et al., 2019) or carbon capture and storage technologies (Davis et al., 2018; Lau et al., 2021), while some of the existing ones would further grow and expand, e.g. plant-based meat substitutes (Rubio et al., 2021) and electric vehicles (Creutzig et al., 2015; Hill et al., 2019). This would change the structure of the global economy, with implications for production, trade and investment patterns (van Neuss, 2019).

Several earlier studies have looked at the trade implications of climate mitigation policies. Vrontisi et al. (2020) have explored the potential trade implications of meeting Paris Agreement targets by G20 economies. Authors find that global trade declines due to decreasing fossil fuel demand, while the trade of low carbon technologies increases. Aldy and Pizer (2015) have studied the competitiveness impacts of climate mitigation policies, with a particular focus on the United States. They found that energy-intensive industries are more likely to face reductions in output and increases in net imports compared to less energy-intensive sectors. However, impacts of climate mitigation efforts on individual countries' comparative advantage in trade remains largely unexplored area.

One particular organizational aspect of the global economy that has been rapidly developing since 1990s and is expected to be substantially impacted by the future mitigation efforts are the global value chains (GVCs) (Zhan, 2021).[1] Rapid growth in the GVC-related trade was observed between early 1990s and mid-

[1] GVCs represent an organizational pattern, when production stages of individual commodities are separated and distributed across different countries and often continents. Examples of such cases can be found everywhere around us – from cars and cell phones to pens and shoes. Studies show that this phenomenon has been driven by a number of factors among which authors distinguish declining transport and communication costs, increasing technological progress, as well as lower barriers to trade and capital flows (Baldwin, 2013; Amador and Cabral, 2016).

2000s, when a more complex global trade and production structures started to evolve exploiting the differences in factor costs across countries (Figure 1).

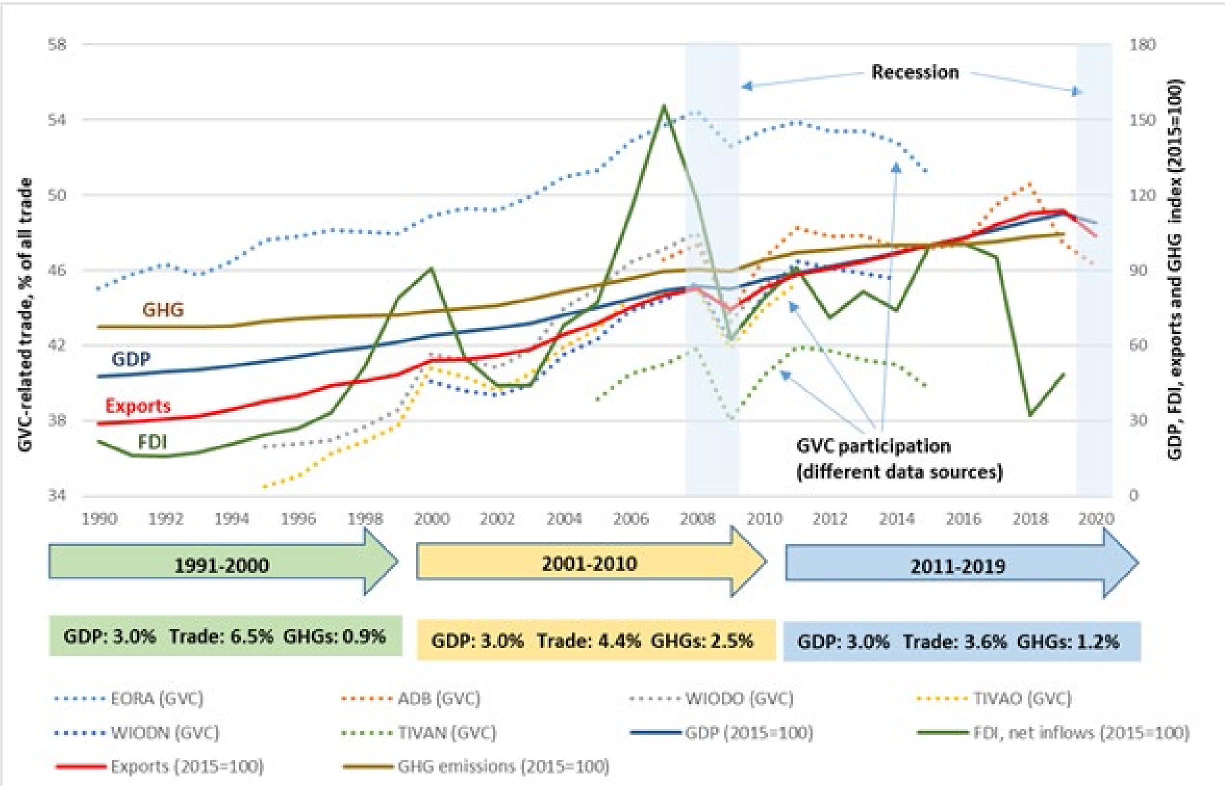

Figure 1. GVC and macro indicators over 1990-2020

Notes: Doted lines represent estimates of GVC-related trade (as a share of total trade – left axis) based on five different datasets. Each dataset is identified by name and covers different time period. Numbers below each arrow under the chart represent annual average growth rates of the indicator during the corresponding period. GVC participation rate is calculated as the sum of domestic value added in the foreign export (forward participation) and foreign value added in domestic export (backward participation).

Source: Estimated by authors using data from Borin et al. (2021) and WB (2022).

Several previous studies have explored the underlying factors of GVCs reshaping in the historical perspective (Baldwin, 2013; Amador and Cabral, 2016; WB, 2020), however, an analysis of how future climate mitigation efforts could affect the restructuring of GVCs across countries remains limited.

Here we address this gap in the literature and focus on a set of exploratory scenarios that represent future climate mitigation policies and measures, including achievement of the nationally determined contribution (NDC) targets, more ambitious mitigation goals consistent with limiting global temperature below 2°C and implementation of the carbon border adjustment (CBA) measures. We look at how these climate mitigation efforts affect different countries' comparative advantage in trade as well as their GVC participation rates.

Overall, our results suggest that with increasing climate mitigation efforts, low carbon intensive sectors, such as electronics and transportation equipment, gain their share in global exports. The extent of such an expansion across countries is largely driven by the reference shares of the corresponding commodities in country's exports and output (reflecting first-mover advantage), as well as carbon intensity of the corresponding production processes across countries. We also find that countries can use specific measures, such as targeted recycling of carbon revenue toward cleaner sectors to incentivize the production of clean goods and services and reduce overall mitigation costs.

In terms GVC participation metrics, our stylized modeling results indicate that while fossil fuels and energy intensive sectors experience a reduction in the GVC participation rates following an implementation of climate policies, service sectors and light manufacturing activities see a moderate increase in their involvement to the global values chains. These include such highly GVC-integrated commodities like computers and electronics, motor vehicles and parts and other light manufacturing goods. Thus, our analysis suggests that the climate mitigation policies stimulate higher integration into the GVCs of low carbon intensive commodities, while economies that specialize in such goods have better opportunities in navigating the low emission development transition.

The rest of the paper is organized as follows. Section 2 provides an overview of the methodological framework, including a discussion of the applied modeling tools and developed global scenarios.

2. Scenarios and methodology

To comprehensively explore the impacts of future mitigation policies, we rely on a multi-model assessment framework, which includes the TIMES Integrated Assessment model (TIAM-WORLD) and global computable general equilibrium (CGE) model ENVISAGE.

Using this suite of modelling tools, we analyze a set of exploratory climate mitigation scenarios. Our scenario framework, first, includes a development of the baseline (or reference) scenario pathway till 2050, within which we assume no targeted climate actions. We then impose a set of exploratory mitigation scenarios on top of the baseline pathway, including nationally determined contributions (NDCs) and their interpretation post-2030, implementation of the set of more ambitious policy scenarios consistent with limiting global temperature increase below 2^{o}C, as well as carbon border adjustment mechanism (CBAM) implemented by the European Union. We also explore alternative revenue recycling mechanisms within the mitigation scenarios.

In this section, we first briefly describe each of the applied modelling tools. We then follow with a discussion of the models' linking approach and close the section with an overview of the scenario assessment framework.

2.1. TIAM-World energy system model

TIAM-World is a multi-region inter-temporal partial equilibrium model of the global energy system. The model is based on The Integrated MARKAL-EFOM System (TIMES) approach (Loulou and Labriet, 2008). TIMES is a full sector cost-optimization model that integrates assumptions across fuel, technology, and policy landscapes to explore how the entire energy system responds to different incentives and constraints. It determines least-cost investment pathways and energy system operation to meet exogenously projected Energy service demands – subject to various energy system and environmental constraints. It is a flexible and modular framework where energy commodity flows are represented in a fully customizable Reference Energy System from primary energy extraction through conversion and production to end use. Technologies are easily added, removed, or represented at different resolutions. Users specify the time periods, regional and sectoral coverage, and coverage of air pollutants. For the electric power sector, demand is modeled through seasonal and daily time slices. Different types of storage technologies can be modeled. TIAM model database is calibrated to the International Energy Agency (IEA) balances' 2019 reference year. Appendix A provides additional details on the technological representation in the TIAM-World model. Regional aggregation of the TIAM model used in the current study is consistent with the regional aggregation of the ENVISAGE modelling framework discussed below. The TIAM-World model is run till 2100 with carbon budgets (temperature targets) imposed over 2070 or 2100 timeframe.

2.2. ENVISAGE model

The Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) model at its core is a recursive dynamic and global CGE model (van der Mensbrugghe, 2019). The model follows a modular set up, where different modules of the framework can be turned on or off depending on the purpose of simulations. ENVISAGE is solved as a sequence of comparative static equilibria where the factors of production accumulate over time. A more detailed description of the ENVISAGE model is provided in van der Mensbrugghe (2019).

The ENVISAGE model used in this study is calibrated to the Global Trade Analysis Project (GTAP) 10 Power Data Base with 2014 reference year, which distinguishes 141 regions and 76 sectors (Aguiar et al. 2019; Chepeliev 2020a). The latter includes 11 electricity generation technologies, as well as an electricity transmission and distribution activity. For the purposes of this study, we use an aggregation that includes 19 regions (Appendix B) and 36 sectors (Appendix C). Model version used for the current assessment assumes full employment. A default assumption is that carbon revenue is recycled to households via direct transfers (a reduction in direct taxes). The Envisage model is run till 2050. The model is complemented by non-CO_2 greenhouse gases (GHGs) (Chepeliev, 2020b) and air pollutant accounts (Chepeliev, 2021).

The core strength of the global CGE models, like ENVISAGE, is a consistent representation of inter-dependencies between sectors, agents and markets within the economy. By capturing both the supply and demand sides, the model represents adjustments in quantities and prices reacting to the policy shock. For instance, if a carbon price is imposed in the model, this leads to increasing energy prices, reducing energy supply and demand, accompanied with structural shifts in the economy – declining share of energy-intensive sectors and expanding low-carbon activities (e.g. light manufacturing and services).

2.3. Model linking

We use a soft-linking approach to couple the models within the current study (Figure 2). First, the TIAM-World model is run to calibrate the baseline path and come up with a set of mitigation scenarios that are consistent with limiting global warming below 2C and 1.5C within the 2070 and 2100 timeframe. As a result, we obtained four mitigation scenarios with varying emission trajectories and carbon budgets over 2019-2050 timeframe. These mitigation pathways are used as boundary conditions when implementing policy scenarios in the ENVISAGE modelling framework. Harmonization is implemented at the global level, as further discussed in the next sub-section.

Next the ENVSAGE model is run to provide an assessment of the socio-economic impacts of various mitigation policies. This provides us with a set of economic indicators, including implications of the considered measures for the competitiveness, trade and restructuring of the global value chains.

2.4. Global scenarios

For the implementation of the baseline scenario, we calibrate the model to pre-defined gross domestic product (GDP) and labor force trajectories. GDP trends are sourced from the International Monetary

Fund’s (IMF) World Economic Outlook (WEO) (IMF, 2021). IMF’s WEO projections cover the period till 2026. To represent the GDP trends post-2026, we rely on the Shared Socioeconomic Pathways (SSP) database, in particular, the OECD-developed SSP2 scenario (Riahi et al., 2018), which corresponds to the “middle of the road” pathway with intermediate socio-economic challenges for mitigation and adaptation.

To capture the expected energy and emission trends within the baseline scenario, we incorporate a set of energy-related assumptions. The latter include declining costs of renewable electricity generation, non-price related changes in preferences towards renewables, increases in electricity shares for the final and intermediate consumers (electrification rates), improvements in energy efficiency, increasing share of services (servitization) and reduction in international transportation costs.[2] Annexes D and E provide additional details on the baseline calibration assumptions.

In addition to the assumptions discussed above, we also implement carbon prices in selected countries and regions, including EU, China and high-income countries. Annex E reports corresponding price trajectories. Carbon prices are imposed on a selected set of energy-intensive sectors that correspond to EU emission trading scheme (ETS) activities. The latter include chemicals, metals, non-metallic minerals, petroleum products, wood products and electricity generation.

We consider six scenarios that explore various aspects of climate mitigation policy. These scenarios cover different levels of climate mitigation ambition across regions, as well as potential configurations of the carbon border adjustment measures (Table 1). Unconditional (“NDC”) Paris Agreement targets are adapted from Kitous et al. (2016). These targets are further aggregated using baseline emissions as weights to match the regional aggregation (Annex B). For selected countries and regions, NDC targets are further adjusted based on the Climate Action Tracker database[3] and taking into account the baseline emission trends. In cases when countries have non-binding NDC commitments, i.e. baseline emission trends already reach stated NDC target, we impose a 5 percent mitigation goal (in 2030 relative to baseline). As a result, based on our interpretation, all countries and regions need to implement additional mitigation efforts under the NDC scenario (compared to the baseline path).

Table 1. Climate policy scenarios in Envisage

No.	Scenario	Description
1.	NDC	Includes a translation of unconditional NDCs into regional emission reduction requirements for 2030 relative to the baseline in 2030. Carbon pricing assumptions are applied post-2030.
2.	NDC-CBAM	Includes NDC scenario with carbon border adjustment mechanism (CBAM) implemented by the European Union. Emission scope and sectoral coverage of the CBAM is expanding over time.

[2] The baseline scenario incorporates a reduction in transportation costs over time due to more efficient modes of transportation, improvements in the energy efficiency of the transportation sector over time, etc. In the various climate mitigation scenarios we run, when we impose carbon prices on the combustion of fossil fuels, the cost of transportation increases relative to the baseline case.

[3] https://climateactiontracker.org/

3.	2C	Regional-specific emission reduction targets for 2030 based on NDCs and a ramping up of mitigation ambitions post-2030 with a harmonization of global carbon prices consistent with limiting global warming at 2°C.
4.	2C-FTAX	"2C" scenario with carbon revenue recycling via reduction of the factor taxes in low-carbon activities, including services, light manufacturing and renewable energy
5.	<2C	Regional-specific emission reduction targets for 2030 based on NDCs and a ramping up of mitigation ambitions post-2030 with a harmonization of global carbon prices consistent with limiting global warming at below 2°C.
6.	<2C-EARLY	Includes an ambitious early climate mitigation action (pre-2030) with setting up of a global carbon price, which allows to achieve more stringent emission reductions compared to the "<2C" scenario. The climate mitigation target in this scenario is consistent with limiting the increase in global temperature to 1.5°C by 2100.

Emission reductions are achieved by the imposition of carbon price, which is endogenously estimated by the model to meet a pre-defined emissions reduction target. Carbon prices are imposed on all emitting agents, including households. Under the NDC scenario, emission reduction targets for 2030 are implemented linearly starting from 2023. For the case of EU, NDC interpretation is consistent with the "FIT for 55" mitigation goal of reducing greenhouse gas emission by 55 percent in 2030 relative to the 1990 level. Considering that this is an ambitious target and in line with the discussion of a broader set of policy instruments within the EU Green Deal package (EC, 2019), we complement the EU mitigation efforts with a number of fiscal policies. These include the removal of production subsidies to fossil fuels and transportation activities (increase of the production taxes to 3%), increase in the sales tax for petroleum products (by 10%), as well as subsidy to renewable generation (5%).

Since NDC targets are specified for 2030, we need to make additional assumptions regarding evolution of mitigation efforts in a post-2030 period. We address this point by imposing an exogenous carbon price trajectory. We assume that in all countries and regions except the EU, carbon prices grow at 5 percent per year, while in the EU an assumed growth rate is 3 percent, considering that this region has the highest carbon price in 2030 based on our implementation. We also impose a minimum of 30 USD per tCO_2 carbon price in 2035 in all countries and regions. Appendix G provides an overview of the carbon price trajectories under the NDC scenario.

Considering a relatively low NDC-based mitigation ambition in most countries and regions in 2030, only a few regions have carbon prices above 30 USD per tCO2 in 2035 (Appendix G). Such exceptions include EU-27, Rest of high-income countries, High-income Asia and Brazil. In the first two cases, carbon prices exceed 240 USD per tCO2 in 2050, while for High-income Asia and Brazil the carbon price is around 110 USD per tCO_2 in 2050. In all other countries and regions, carbon price reaches 62 USD per tCO_2 in 2050.

"NDC-CBAM" scenario is an "NDC" scenario, where European Union countries implement the CBAM starting from 2026. The CBAM is implemented as an excise tax imposed on region- and commodity-specific carbon content of imports to the EU. The carbon price level that is used to determine the CBAM rate is estimated as the difference between the carbon price in the EU and the carbon price in the country/region of the imported commodity origin. Between 2026 and 2030 it is assumed that the CBAM covers Scope 1 emissions from chemicals, metals and electricity generation sectors. Between 2031 and 2035 the CBAM is extended to Scope 2 emissions with the same commodity coverage. Starting from 2036 the CBAM is imposed on Scopes 1, 2 and 3 emissions, while commodity coverage is expanded to all EU ETS sectors.

“2C” scenario includes NDC policies and measures till 2030 and an implementation of a more ambitious policies in a post-2030 period. In particular, it is assumed that starting from 2035 all countries apply uniform carbon prices that are equal to the EU carbon price trajectory within the NDC scenario (Annex G). As a result, by 2050 all countries face the carbon price of $248 per ton of CO2. It should be noted that within all analyzed scenarios, the carbon prices are imposed on CO2 emissions from fossil fuels combustion only.

“2C-FTAX” scenario assumes the same carbon mitigation trajectories as in the “2C” scenario, but relies on a different revenue recycling scheme. While “2C” scenario uses an approach where carbon revenue is recycled to the households via direct transfers (a reduction in direct taxes), “2C-FTAX” scenario uses carbon revenue to reduce factor taxes in selected sectors. Sectors that face corresponding tax reductions are investment-generating activities (construction), GVC-integrated low-carbon intensive activities with high value added (electronics, electrical equipment, textile and wearing apparel, vehicles, metal goods and transport equipment) and clean energy (solar, wind and other renewable power generation).

“<2C" scenario explores a more ambitious mitigation pathway consistent with efforts of limiting global warming well below 2^{o}C. Such efforts envisage NDC-consistent policies till 2030 and a rapid increase in carbon prices in the post-2030 period. Global carbon price is set at $159 per ton of CO2 in 2035 and grows at around 6% per year to reach $393 per ton of CO_2 in 2050.

However, as analysis suggests, even such an effort is not consistent with limiting global warming below 2^{o}C. Therefore, we design a scenario with early action, where global uniform carbon prices are being implemented starting from 2024 at the level of $43 per ton of CO_2. They further grow at almost 7% per year to reach $471 per ton of CO_2 in 2050. Due to the implementation of an early mitigation action, we label this scenario “<2C-EARLY” and this scenario is consistent with limiting the increase of global temperature to 1.5^{o}C by 2100. Appendix H offers an overview of the carbon price trajectories under the “<2C” and “<2C-EARLY” scenarios.

In TIAM model, four policy scenarios are considered. They differ in terms of mitigation ambition and the timeframe over which the specified carbon budget is reached (Table 2).

Table 2. Climate policy scenarios in TIAM

No.	Scenario	Budget period	Budget, Gt	Scenario description
1.	2C-2070	2020-2070	1310	2^{o}C-consistent scenario with carbon budget imposed over 2020-2070 period
2.	2C-2100	2020-2100	1310	2^{o}C-consistent scenario with carbon budget imposed over 2020-2100 period
3.	1.5C-2070	2020-2070	460	1.5^{o}C-consistent scenario with carbon budget imposed over 2020-2070 period
4.	1.5C-2100	2020-2100	460	1.5^{o}C -consistent scenario with carbon budget imposed over 2020-2100 period

Figures 2 and 3 below provide an overview of the emission trajectories and carbon budgets across the applied modelling frameworks and scenarios within the 2019-2050 timeframe.

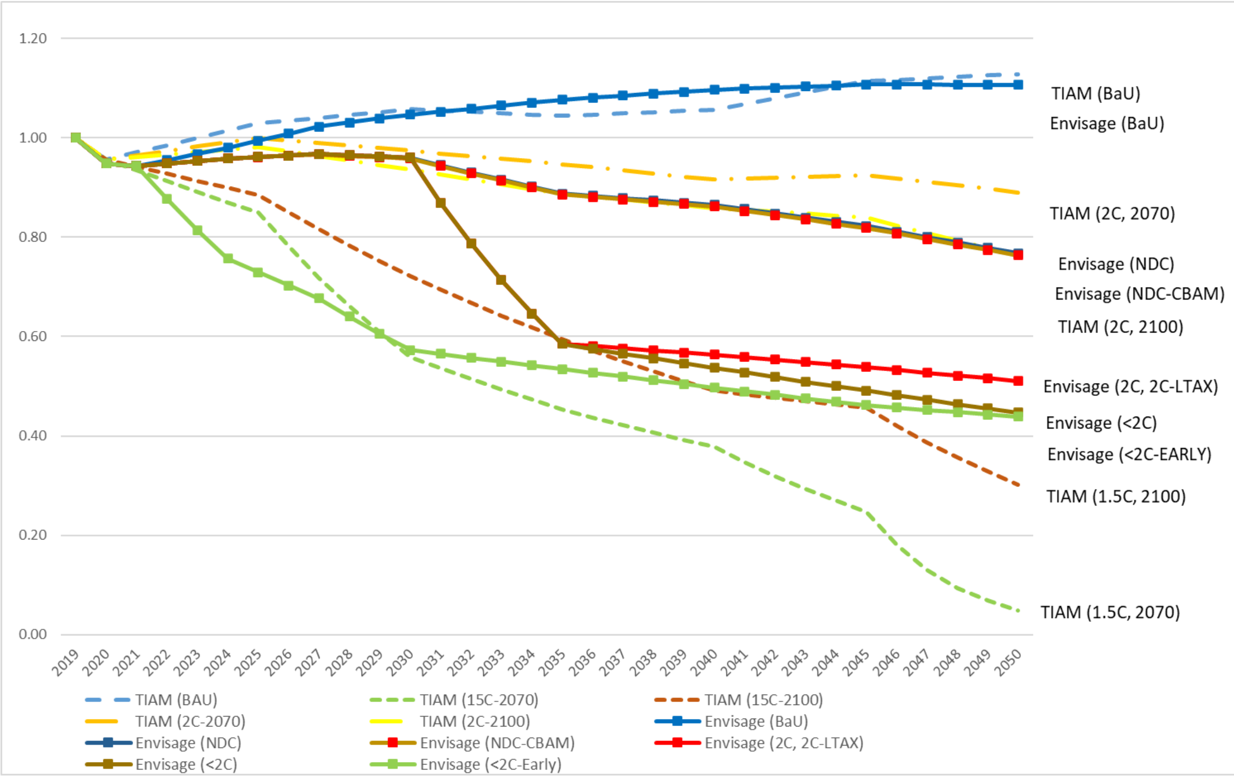

Figure 2. Emission trajectories in TIAM and Envisage, 2019=1

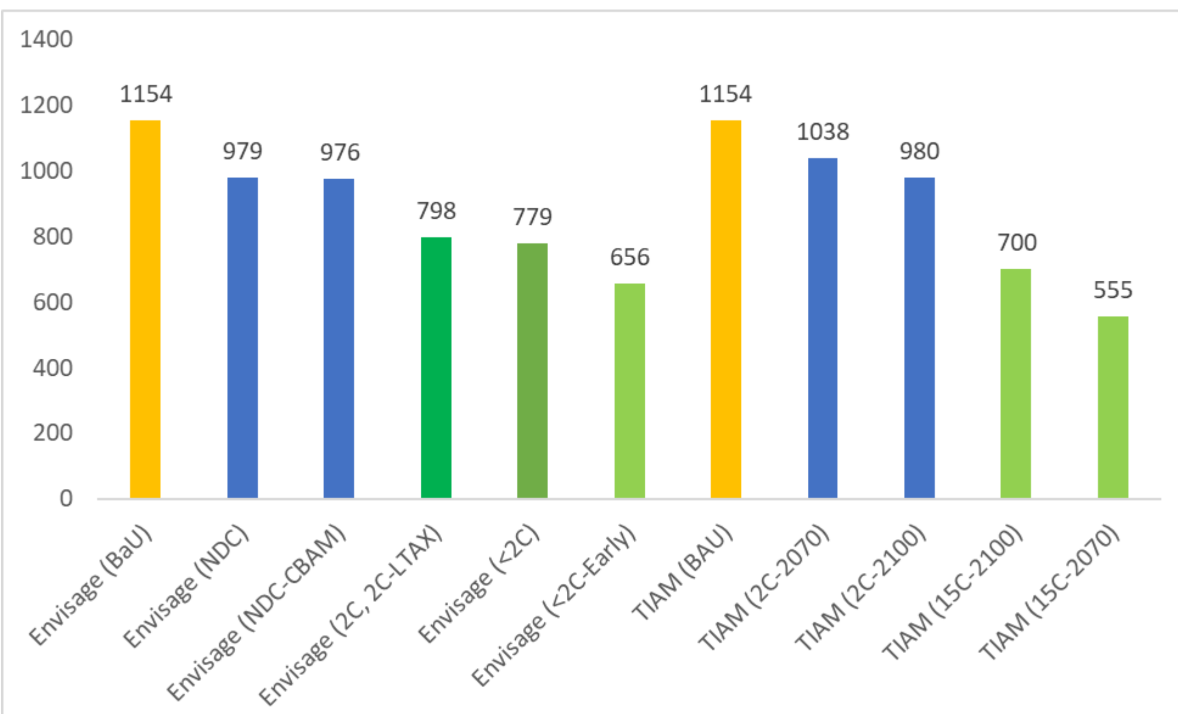

Figure 3. Carbon budgets across scenarios and models, Gt (2019-2050 cumulative)

3. Results

3.1. Impacts on production and trade are shaped by transformations in global energy system

Achievement of the stringent mitigation targets would be accompanied by changes in the global energy system and economy. Magnitude of impacts varies across mitigation scenarios (Figure 4), but a general trend is an increase in the share of carbon-free electricity (solar, wind, nuclear, hydro and other renewable energy sources) in the overall output structure – in a range of 0.5%-1.1% depending on scenario and an increase in the share of service sectors (trade, financial services, tourism, etc.) – in a range of 0.2%-0.8% (Figure 4). At the same time, a reduction in the share of fossil-based electricity and fossil fuels is observed. With overall increasing electricity demand due to the substitution of direct fossil fuel use by electricity (e.g. shift toward electric vehicles in the transportation sector or electrification of home heating and cooking), the growth in renewable electricity generation is overcompensating the reduction in the fossil-based electricity supply. Manufacturing activities are moderately impacted by the implemented mitigation efforts. In particular, light manufacturing is expanding its share in the aggregate output by up to 0.1% in the case of "2C-FTAX" scenario (Figure 4), where part of carbon revenue is recycled to the light manufacturing activities in a form of reduced factor taxes.

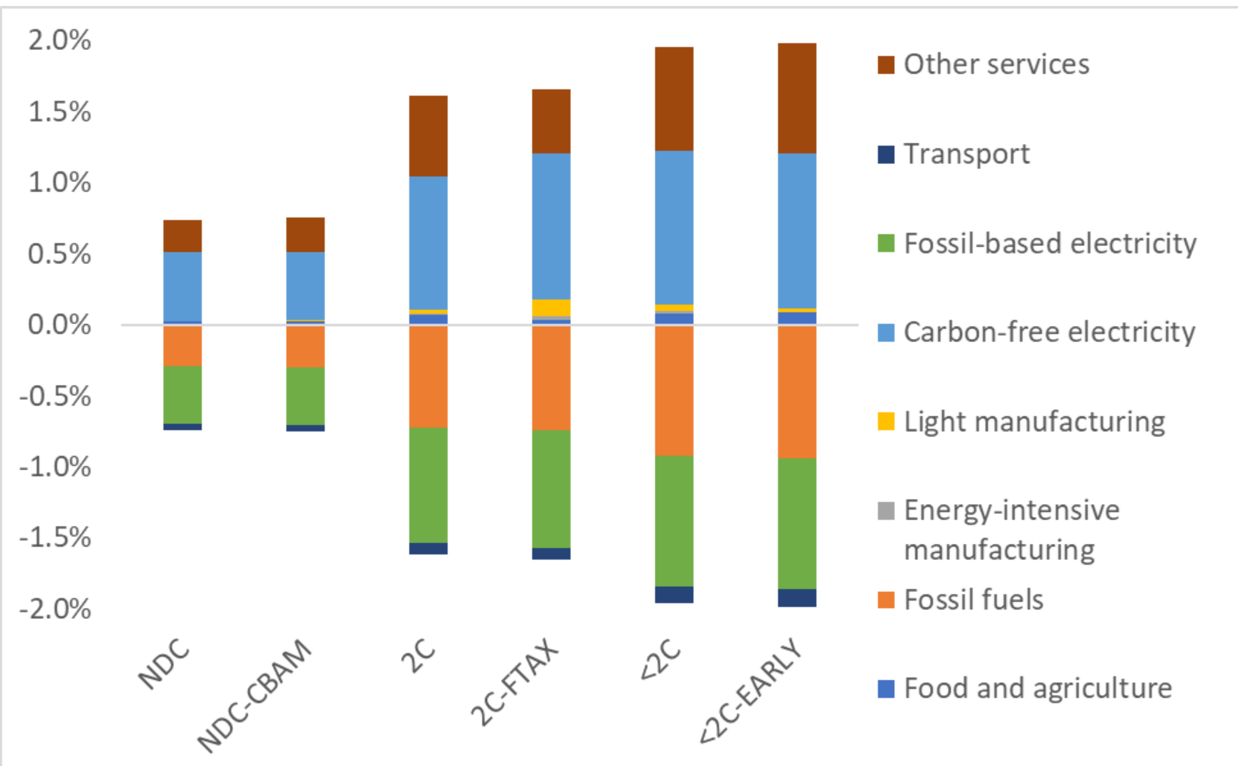

Figure 4. Change in the shares of global output relative to baseline in 2050, percentage points

Electricity generation sector is the one that faces the most substantial structural transformations due to the rapid substitution away from emission-intensive and toward carbon-free technologies. In addition, though not explicitly observed within the applied modelling framework due to the aggregation bias, selected sectors would go through major compositional changes. For instance, motor vehicles production would be moving away from internal combustion cars and toward electric vehicles (EVs); electronics and electrical equipment activity would be ramping up the output of components needed in solar and wind-power generation, as well as EVs' production process; metal products sector would be substantially expanding the supply of inputs needed for the wind turbines installation.

While these complex value chains are not explicitly disaggregated in the ENVISAGE modelling framework, an overall magnitude of the anticipated changes can be implied from the observed transformations within the electricity generation activity. Since TIAM model covers the horizon till 2100, this allows us to explore changes in the generation mix over the longer timeframe than simulated in ENVISAGE (Figure 5). As results suggest, under the "2C-2100" scenario solar power generation is expanding over 31 times between 2019 and 2050, while wind generation grows 3.4 times over the same period (Figure 5a). Even more dramatic expansions over the same period are observed under a more ambitious 1.5C-2100 scenario, as solar power generation increases by over 46 times, while wind power grows by almost 5 times (Figure 5b). This implies that, for instance, the global output of solar panels needs to increase in a range of 30-40 times by 2050 compared to the currently observed level in order to support such an energy system transition. Looking beyond 2050 timeframe, one could anticipate the need of even more dramatic transformations in supply chains, as the output of solar power grows by over 180-210 times across scenarios.

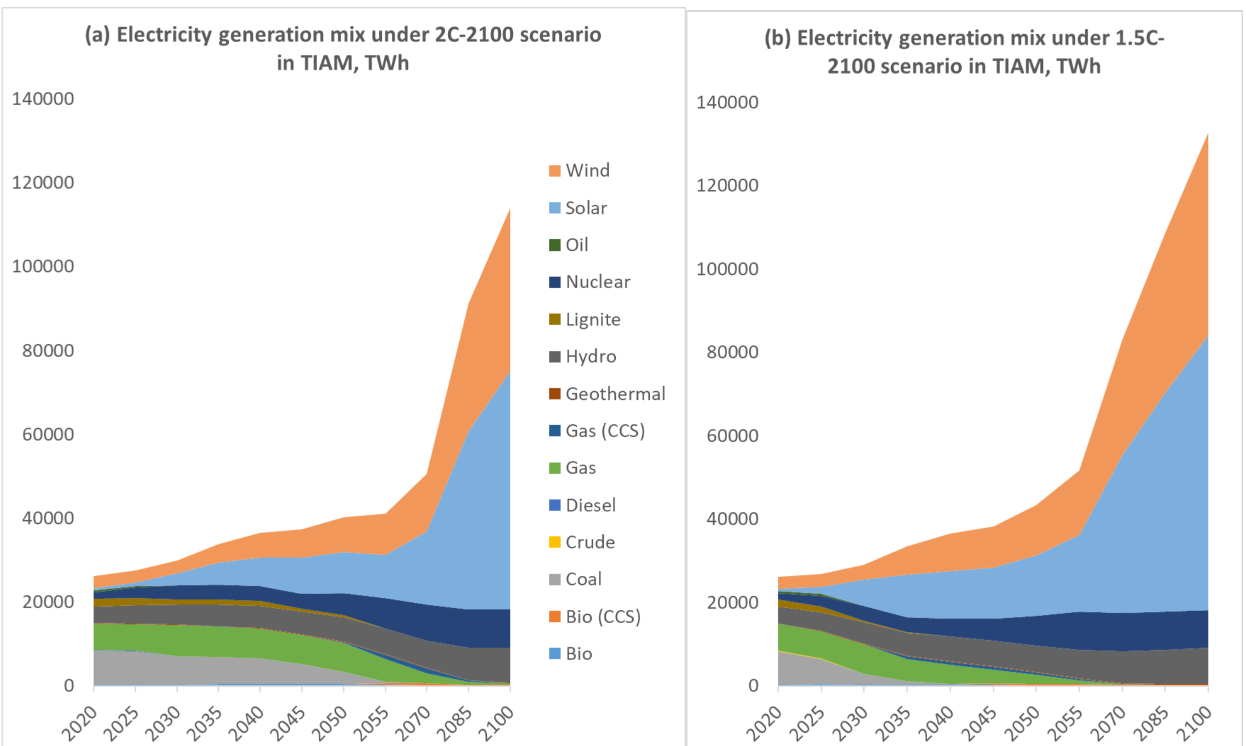

Figure 5. Global electricity generation mix in the TIAM model under 2C-2100 (a) and 1.5C-2100 (b) scenarios, TWh

With respect to individual country-level results, under the 1.5C-2100 scenario, from 2020 to 2050, the United States moves away from using coal, oil and gas in generating electricity and towards using renewable electricity generation, in particular, wind and solar (Figure I.1, Annex I). Solar power generation increases by over 10 times from 2020 to 2050 and wind power generation increases over 11 times during the same period (Figure I.1, Annex I). When it comes to the EU, the EU-27 countries also divert away from using coal, gas and oil in generating electricity and moves into using renewable energies, including wind and solar to generate electricity (Figure I.2, Annex I). Solar power generation increases by over 4 times from 2020 to 2050 and wind power generation more than doubled during the same period (Figure 7). Our modeling results suggests that if unconstrained by political decisions, nuclear power generation in the EU could expand substantially between 2020 to 2050 (by over 16 times) (Figure I.2, Annex I).

Results for developing countries show a similar trend: in the case of India, for example, under the 1.5C-2100 scenario, the country moves away from using coal, gas and oil in generating electricity and shifts toward renewables. India's solar power generation is expected to increase by over 46 times from 2020 to 2050, as the country has high index of solar radiation, while its wind power generation is anticipated to increase by over 3 times during the same period. (Figure I.3, Annex I).

With stringent mitigation efforts, especially in the second half of the century, new energy commodity markets are arising. In power generation, hydrogen is considered one of the leading options in storing renewable energies (IEA, 2019). Our results suggest that the global hydrogen trade is anticipated to expand significant starting from 2050, with the United States being the leading exporter, and China and India being the key importers (Figure I.4, Annex I).

3.2. Low carbon transition would require major policy efforts, but the costs are manageable and the co-benefits are substantial

While policy efforts required to put the global economy on the low carbon transition pathway could be challenging to implement (Pahle et al., 2018; Keohan and Victor, 2016), if the society would succeed in this, an overall cost of such transition would be rather moderate. Even under the most ambitious "<2C-EARLY" scenario, global GDP declines by only 1.4% in 2050 relative to baseline (Table J.1, Annex J), which, if translated to the annual growth rate, corresponds to a slowdown of around 0.05% per year. Less ambitious mitigation scenarios would result in even lower global GDP costs – ranging between 0.5% and 1.1% (Table J.1, Annex J). Associated welfare losses are even lower than the estimated reductions in GDP and range between 0.4% and 0.8% (Table J.2, Annex J). Variation in mitigation costs across countries is driven by the socio-economic characteristics of each economy – production and trade profiles, emission intensity, energy mix, etc.

Consistent with earlier literature (e.g. Freire-González and Ho, 2019; Chen et al., 2020), results from the current assessment suggest that recycling carbon revenue in the form of reduced factor taxes, as opposed to the direct lump-sum payments, can decrease overall economic costs of transition, as well as reduce carbon prices needed to achieve the defined mitigation targets. As can be seen from the comparison of "2C" and "2C-FTAX" scenarios, carbon revenue recycling via reduced factor taxes on low-carbon activities, including services, light manufacturing and renewable energy, reduces the mitigation costs by almost two times – from 0.9% to 0.5% of global GDP (Annex I). In the case of low- and middle-income countries (LIC), the benefits are even more substantial – a reduction from 0.9% to 0.3% and if LICs are considered excluding China, then the GDP cost is virtually 0. Factor tax recycling option, in fact, could even lead to net welfare-improving outcomes for this group of countries (Table J.2, Annex J).

It should be noted that these costs are measured without taking into account mitigation-related co-benefits such as improved air quality (Markandya et al., 2018; Vandyck et al., 2018; Xie et al., 2018), decreased pressure on water resources (Bergesen et al., 2014; Gibon et al., 2017) and improved biodiversity (Albano et al., 2021; Urban, 2015). These co-benefits would come on top of the reduced climate-related damages, as well as lowered frequency and magnitude of catastrophic weather events

(Ornes, 2018; Tol, 2018). Earlier studies suggest that if accounted for, in many cases, such impact channels could lead to net welfare and GDP gains (e.g. Markandya et al., 2018; Vandyck et al., 2018).

To showcase this point, we link changes in air pollutant emissions across countries and regions generated by the ENVISAGE model with the TM5-FASST global atmospheric source-receptor model (van Dingenen et al., 2018). Such model link allows us to associate changes in each air pollutant emissions with seven types of diseases identified in the TM5-FASST model: ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), stroke, lung cancer (LC), lower respiratory airway infections (LRIs) and diabetes mellitus type 2 (DMT2), O3 respiratory diseases. We then estimate mortality rates due to each of these diseases and aggregate these estimates over all air pollutants, explicitly assessing the health co-benefits of the climate mitigation policies across considered countries and regions.

Results suggest that under the “2C” scenario, a reduction in air pollution due to low carbon development can save almost 740,000 lives in 2050, when compared to the reference scenario (Figure 10). When compared across countries, both in absolute terms and per million of population, India benefits the most from the reductions in air pollution, as around half of all saved lives worldwide occur in this country. In relative terms, China, the Rest of South Asia, the United States, the Rest of East Asia, High Income Asia and Türkiye all have at least 70 lives saved per million. Across diseases, almost half of all premature mortality reductions are associated with chronic obstructive pulmonary disease, with lower respiratory infection being the second most impactful factor (Figure 10). “NDC” scenario results in around half of the air pollution-related co-benefits compared to the “2C” pathway with around 333,000 total lives saved in 2050 (Annex K).

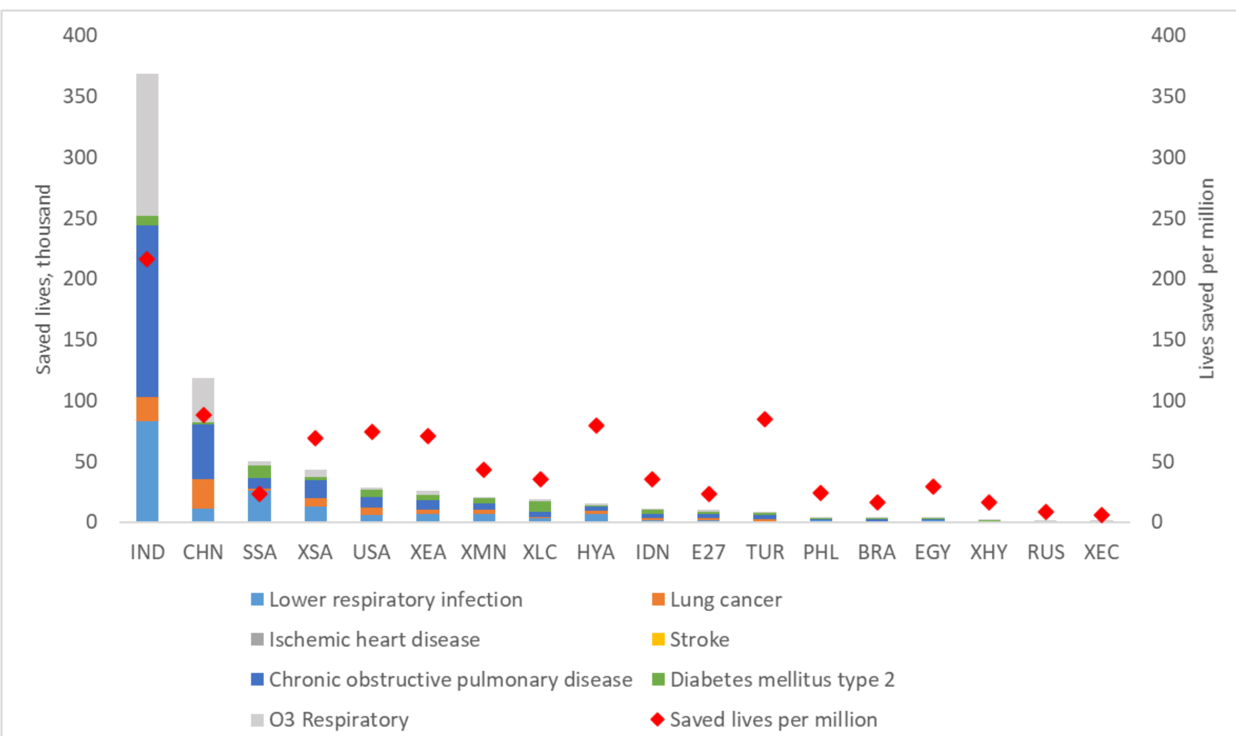

Figure 10. Mortality reductions due to improved air quality under 2C scenario in 2050

To monetize the health co-benefits of improved air quality we rely on the value of social life (VSL) approach outlined in Markandya et al. (2018). In brief, a method uses "unit value transfer approach", which adjusts VSL estimates of the OECD countries to other countries based on the differences in GDP per capita and projected growth rates. Values of the VSL for OECD countries used in this study vary from 1.8 million USD per capita and 4.5 million USD per capita measured for 2005 reference year following Holland et al. (2014).

Results suggest that under the "2C" scenario aggregate air pollution reduction health co-benefits outweigh mitigation costs by over a factor of two (Figure 11). A larger ration of co-benefits relative to mitigation costs is observed for developing countries compared to high-income economies since on average the latter have lower emission intensities and higher costs of emission reduction. In absolute terms, China and India show the largest mitigation co-benefits under the "2C" scenario – in a range of around 400 billion USD combined (Figure 11). On average, low- and middle-income countries excluding China show a ratio of co-benefits to mitigation costs of almost five. There are, however, several developing countries/regions, where the corresponding co-benefits do not outweigh the welfare costs. Corresponding examples include the Philippines, Sub-Saharan Africa, Egypt, Eastern Europe and Central Asia.

Under the less ambitious "NDC" scenario, the ratio of air pollution co-benefits to mitigation costs is lower than under the "2C" case, and is around 1.5-2 both for the group of high-income and developing countries. This suggests that a higher level of mitigation ambition is more economically feasible (when compared to the less ambitious "NDC" scenario) once air pollution co-benefits are taken into consideration.

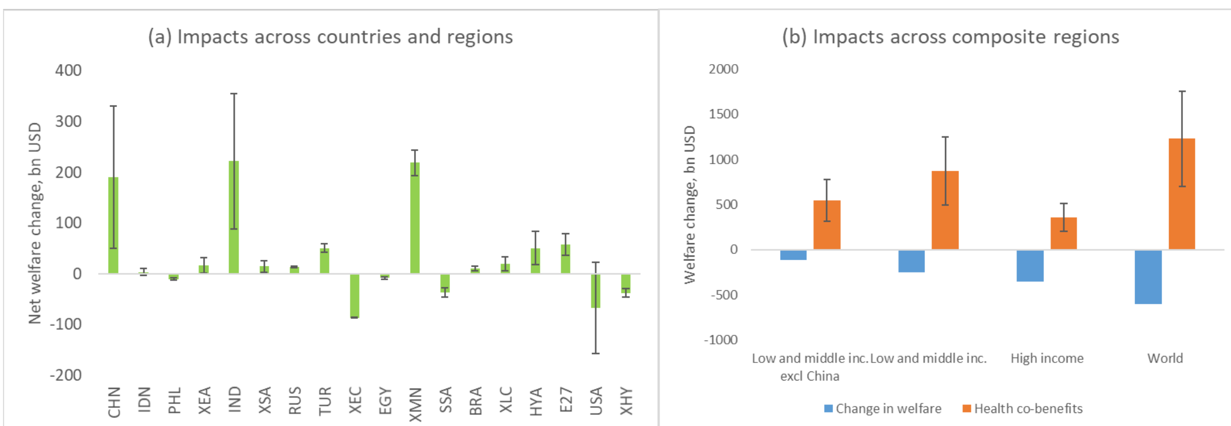

Figure 11. Health co-benefits and mitigation costs under 2C scenario in 2050, billion USD

Notes: Uncertainty bars correspond to lower and upper values of the VSL considered in the analysis. Panel (a) represents impacts across countries and regions modeled in the study. XMN region includes Morocco. Panel (b) reports results for the composite regions. Negative numbers in the case of welfare change correspond to welfare improvement.

3.3. Trade-to-GDP ratio declines and the trade in fossil fuels is impacted the most adversely

Implementation of the mitigation scenarios leads to the reduction in demand for fossil fuels and increasing costs of energy and energy-intensive intermediate inputs. Increasing production costs lead to the contraction in exports from low- and middle-income countries in a range of 1.6%-6.9% across scenarios, with impacts being more substantial under higher mitigation ambition (Figure 12a). High-income countries experience lower magnitude of export reductions – in a range of 0.7%-2.9% (Figure 12b). In case of both groups of countries trade volumes contract more substantially than GDP and as a result the trade-to-GDP ratio falls (Figure 12).

With an overall reduction in the volumes of trade, a change in the composition of exports and imports is observed. In the case of low- and middle-income countries, the share of fossil fuels falls by 0.8-3.7 percentage points (Figure 12a) and an increase in the share of exports across all other sectors is observed. The only exception is the "NDC-CBAM" scenario, where in addition to the falling share of fossil fuels, a reduction in the share of energy intensive manufacturing (chemicals, metals, non-metallic minerals, etc.) is observed. The latter is largely driven by an imposition of the EU's CBAM that targets corresponding commodity group. In the case of high-income countries, in addition to fossil fuels, a reduction in the share of transportation services' export is also observed, as the latter is partly substituted by exports from low- and middle-income countries.

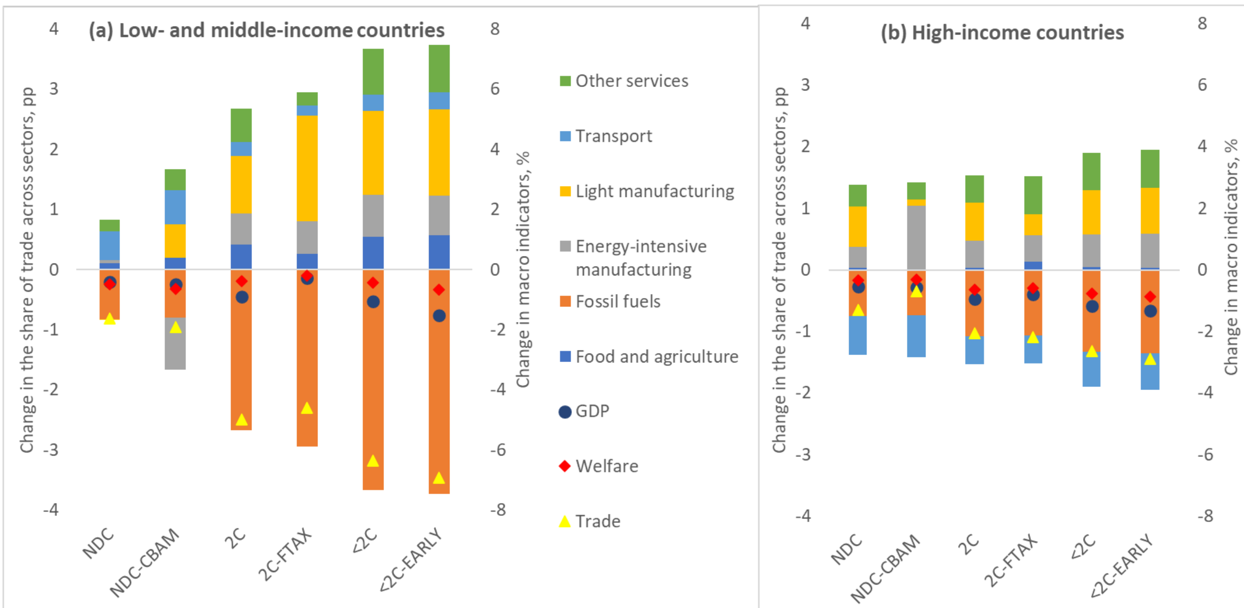

Figure 12. Changes in global sectoral export shares and key macro indicators across scenarios and country groups relative to the baseline scenario in 2050

Notes: Changes in the share of sectoral exports in total exports are measured relative to the baseline scenario and reported in percentage points using stacked bars on the left/primary vertical axis. Panel (a) represents impacts across low- and middle-income countries and regions. Panel (b) reports changes for the group of high-income countries. Changes in macro indicators (GDP, welfare and trade) are reported on the right/secondary vertical axis.

3.4. Exports of electronics and transport equipment gain the largest export share, but impacts depend on policy responses

Exploring the country-level impacts of the mitigation policies on trade, a substantial variation across scenarios is observed, driven both by the level of mitigation effort and specifics of the policy responses (Figure 13, 14 and 15). In the case of "NDC-CBAM" scenario, while the overall magnitude of trade implications is lower than under other more ambitious mitigation efforts, energy-intensive sectors that face the CBAM, such as chemicals, in some cases face even more adverse impacts than fossil fuels (Figure 13). Latter is the case, for instance, in Rest of MENA, Russia, Egypt, India and Rest of South Asia, where a reduction in the share of chemicals is even more substantial than in fossil fuels.

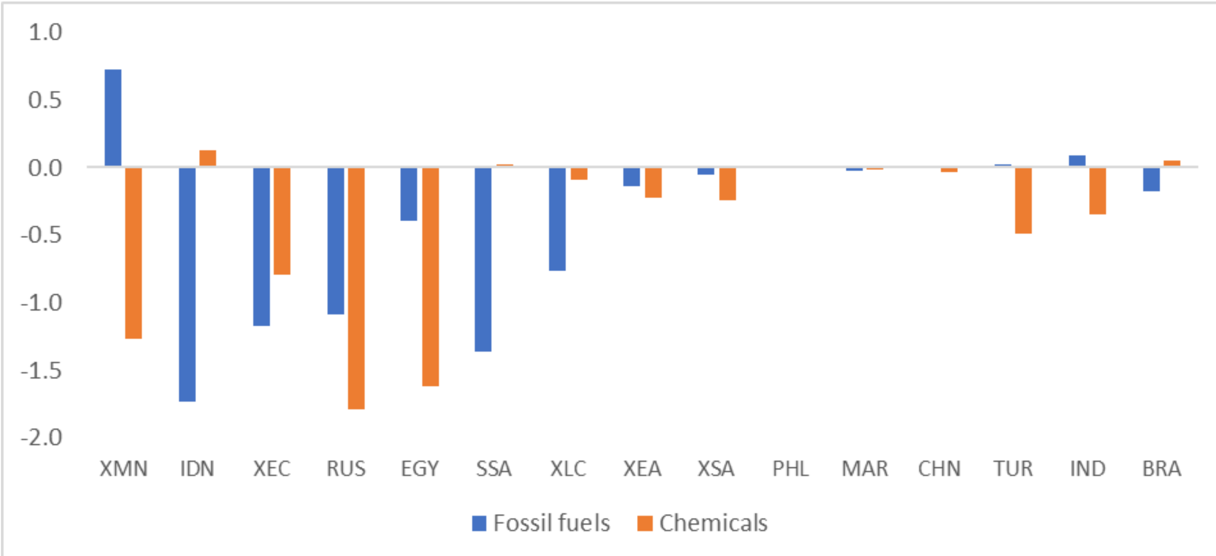

Figure 13. Changes in sectoral export shares across low- and middle-income countries, under the "NDC-CBAM" scenario, in 2030 relative to the baseline.

Notes: Changes in the share of sectoral exports in total exports are measured relative to the baseline scenario and reported in percentage points.

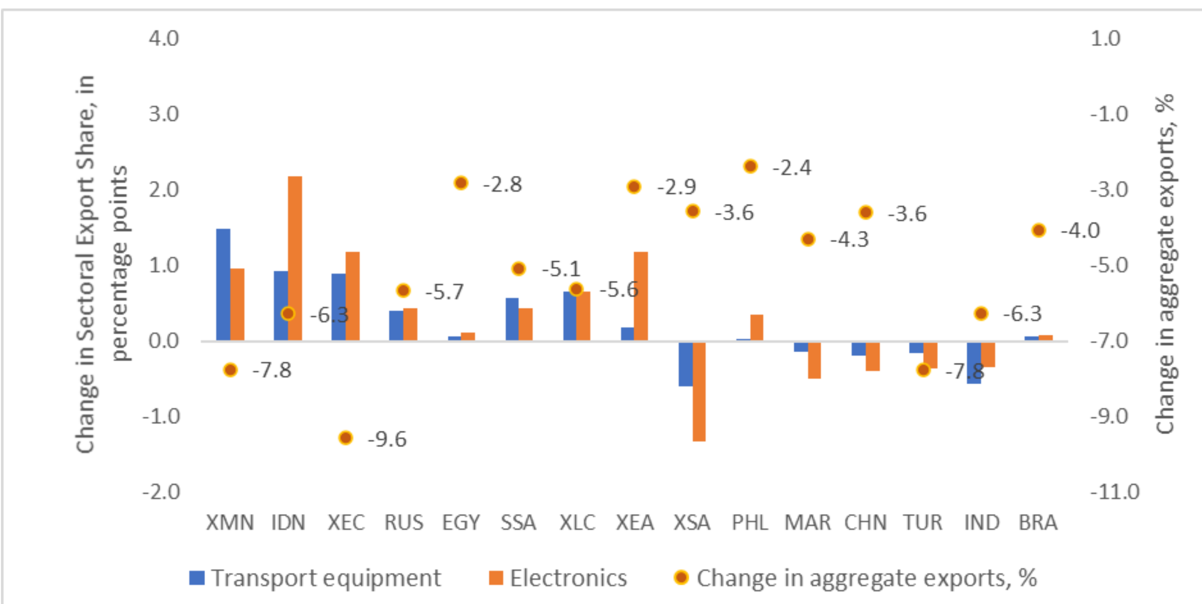

Figure 14. Changes in sectoral export shares and aggregate exports across low- and middle-income countries and regions, under the "2C" scenario relative to baseline in 2050

Notes: Changes in the share of sectoral exports in total exports are measured relative to the baseline scenario and reported in percentage points using bars. Changes in aggregate exports relative to the baseline path are reported in percent using red dots.

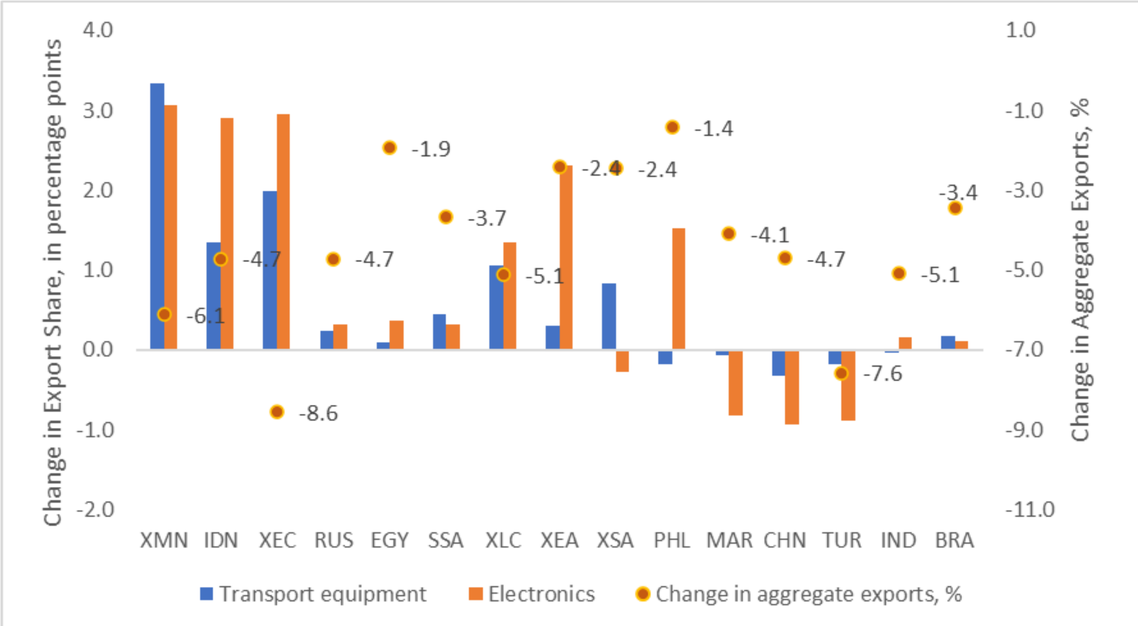

Figure 15. Changes in sectoral export shares and aggregate exports across low- and middle-income countries and regions, under the "2C-FTAX" scenario relative to baseline in 2050

Notes: Changes in the share of sectoral exports in total exports are measured relative to the baseline scenario and reported in percentage points using stacked bars. Changes in aggregate exports relative to the baseline path are reported in percent using red dots.

The extent to which low carbon intensive sectors gain their share in exports largely depends on the carbon revenue recycling approach. In the case of "2C" scenario, where carbon revenue is recycled via direct payments to households, one observes a relatively moderate extent of increasing share of electronics in the total exports – not exceeding 1 percentage point in most countries/regions (only in the case of Indonesia an increase of 2 percentage points is observed) (Figure 14).

In the case of "2C-FTAX" scenario, where carbon revenue is used to reduce factor taxes in low-carbon activities, including services, light manufacturing and renewable energy, one can observe that clean sectors, like electronics and transport equipment, gain substantially larger shares compared to the "2C" scenario discussed above. In Indonesia, Rest of MENA, Rest of ECA and Rest of East Asia, the share of electronics in total exports increases by around 2-3 percentage points (Figure 15). Carbon revenue recycling via reduced carbon taxes also limits an overall magnitude of adverse trade implications, as production costs for selected sectors are being reduced. For instance, looking at the case of Indonesia, aggregate exports under the "2C" scenario fall by around 6.3% (relative to baseline in 2050), while under the alternative revenue recycling case ("2C-FTAX" scenario), aggregate exports decline by only 4.7%.

3.5. Understanding Changes in Exports of Non-Energy Intensive Products: A Case of Electronics

With a growing mitigation effort, there is an overall decline in the trade-to-GDP ratio. As a result, global exports (in volume terms) of non-energy intensive products, such as electronics, transportation equipment, grains and oilseeds, and construction services, experience a small decline. The decline is driven by: 1) countries who are relatively more energy-intensive in producing such products compared to their competitors — for instance, the CO_2 emission intensity of China and India's transportation equipment exports are much higher compared to countries such as the United States, which contributes to the decline of Chinese and Indian exports of transportation equipment under the “<2c early” scenario compared to the baseline; 2) countries who are relatively more energy-intensive in producing such products compared to the average emission intensity for all products in that country — for instance, the average CO2 emission intensity of all Brazilian exports in 2014 is 1.1 kg/USD. Since the CO_2 emission intensity of Brazilian exports of grains and oil seeds (1.5 kg/USD) is higher than the average CO_2 emission intensity of all Brazilian exports, Brazil moves away from producing and exporting grains and oil seeds with a growing climate mitigation effort. By contrast, countries who use relatively “cleaner” resources to produce non-energy intensive products experience an increase in their exports — for instance, the SSA region experiences an increase in its exports of grains and oil seeds, as the region’s CO_2 emission intensity in grains and oil seeds exports is lower compared to its counterparts.

Focusing on the case of electronics, as the most GVC-integrated sectors, the results suggest that global exports of this group of products decline by 3.0 percent under the “<2C early” scenario compared to the baseline in 2050 (figure 16). The decline is primarily driven by China (-2.0 percent), high income Asia (-1.0 percent) and India (-0.3 percent), while advanced economies such as the United States see a small increase in its electronics exports (0.5 percent). Figure 16 also shows the CO_2 emission intensity of individual countries. In general, higher CO_2 emission intensity makes that country’s electronics exports becoming relatively less competitive on the international market. In 2014, CO_2 emission intensity for China and India’s electronics exports was 2.02 kg/USD and 2.90 kg/USD respectively, while CO_2 emission intensity for U.S. electronics exports was 0.94 kg/USD. With the climate mitigation policies, China and India’s electronics exports become relatively less competitive on the international market while the U.S. electronics exports becomes more competitive. The geographical composition of the GVCs also play an important role in determining the restuls. For high income Asia (HYA) countries, 40.7 percent of its electronics exports (mainly intermediates) goes to China in 2014. Therefore, though HYA countries have a relatively low CO_2 emission intensity for electronics exports (1.00 kg/USD), a decline in Chinese exports of electronics products result in a decline in HYA exports of electronics. The change in global export pattern of electronic products is also driven by within country differentials in CO_2 emission intensities across all sectors/activities. In the United States, for instance, the average CO_2 emission intensity for all U.S. exports is 1.14 kg/USD. Since the CO_2 emission intensity for U.S. electronics exports is lower compared to the average CO_2 emission intensity for all U.S. exports, the United States shifts towards producing and exporting more electronics products with a growing climate change mitigation effort.

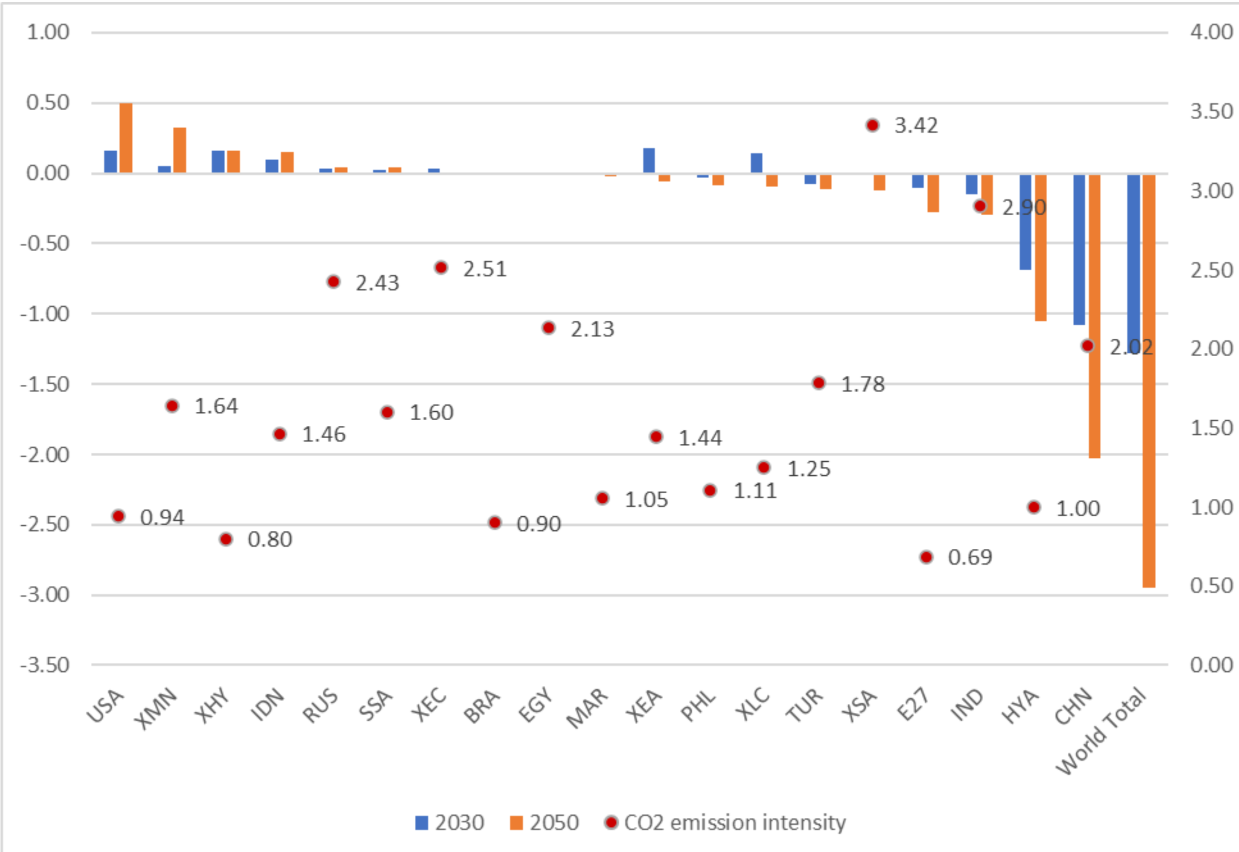

Figure 16. Exports of Electronics Products, by Country, contribution to % change in 2030 under the "<2C early scenario", relative to the baseline; contribution to % change in 2050 under the "<2C early scenario", relative to the baseline. Results are reported in percent changes; CO2 emission intensity in 2014 by Countries and Regions (in kg/USD).

3.6. GVC participation increases with a growing ambition of mitigation efforts

One of the specific features of the applied modeling framework is the differentiation of the commodities by the end user (an MRIO-type specification as discussed above). The model also includes a special module that reconstructs the global MRIO database post-simulation and estimates a number of GVC-specific metrics, including forward and backward linkages, as well as GVC participation rates. It is important to understand how mitigation policies might reshape the GVC landscape since the extent, and nature, of integration into GVCs has important implications in terms of GDP growth, jobs and poverty reduction (World Bank, 2019). Using the GVC participation rate as a representative metric, we assess the potential implications of ambitious mitigation policies. The results suggest that declining trade in fossil fuels is substituted by trade in commodities in which GVCs are more intensive, such as electronics, transport equipment, metal products, and chemicals, leading to an increase in the global GVC participation rate by about 1.2 percentage points under the most ambitious "<2C-EARLY" scenario. As their mitigation efforts increase, countries reduce the production, consumption, and trade of fossil fuels and instead rely more on domestically produced renewable energy sources. At the same time, production and trade in relatively low-emissions-intensive, high-value commodities such as light manufacturing are reduced much less in relative terms. These commodities are characterized by much more advanced and geographically distributed value chains; thus, the average complexity of global supply chains increases.

GVC participation in the low-carbon intensive sectors increases with a growing ambition of mitigation efforts (Figure 17). For instance, the GVC participation rate for the electronics sector increases by 0.08 percentage points in the NDC scenario compared with the baseline; by 0.16 percentage points in the NDC-CBAM scenario; 0.25 percentage point in the 2C scenario; and by 0.33 percentage points in the <2C and <2C-early scenario. Meanwhile, less-emissions intensive sectors with a higher initial participation rate, such as electronics, see bigger increases in GVC participation with a growing ambition of mitigation efforts. By contrast, those with relatively low initial GVC participation rate, such as the wood products sector, experience only a slight increase in GVC participation. GVC participation rates for the emissions-intensive sectors, most notably the fossil fuels sector, declines with a growing mitigation effort.

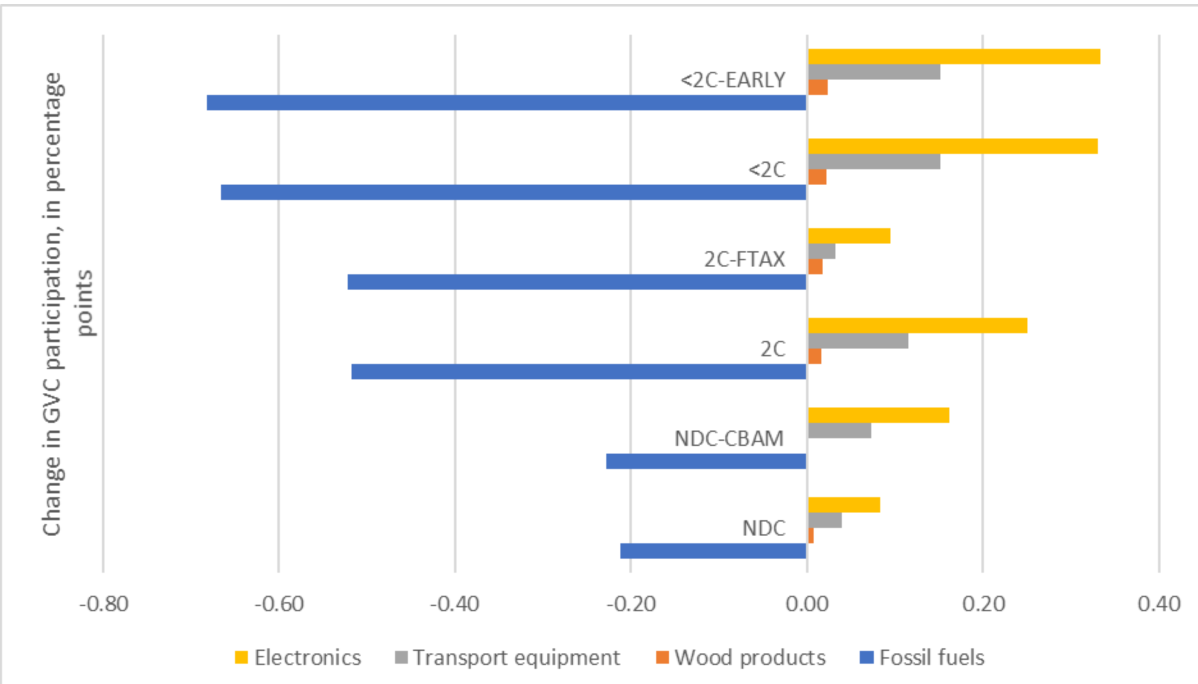

Figure 17. Percentage points changes in the global value chain participation rate relative to the baseline scenario in 2050

Developing countries' participation in GVCs increases the most in transport services and electronics and rises with climate mitigation ambition. For instance, GVC participation in transport services in Egypt, Rest of South Asia, Rest of Middle East and North Africa as well as Morocco increase the most in 2050 compared to the baseline in the "<2C early" scenario, while the GVC participation of electronics in Indonesia, rest of Middle East and North Africa, as well as Rest of Europe and Central Asia increases the most in 2050 in the "<2C early" scenario compared to the baseline (see Figure 18 and Figure 19). Moreover, the magnitude of increase in GVC participation rises with growing climate mitigation effort. Taking the electronics sector in Indonesia as an example — the GVC participation increases by 1.2 percent in the NDC scenario, 1.5 percent in the NDC-CBAM scenario, 2.7 percent in the 2C scenario and 3.3 percent in the "<2C early" scenario. Similarly, in the transport services sector, the GVC participation in Egypt increases by 2.2 percent in the NDC scenario, 2.8 percent in the NDC-CBAM scenario, 3.6 percent in the 2C scenario and 5.49 percent in the "<2C early" scenario.

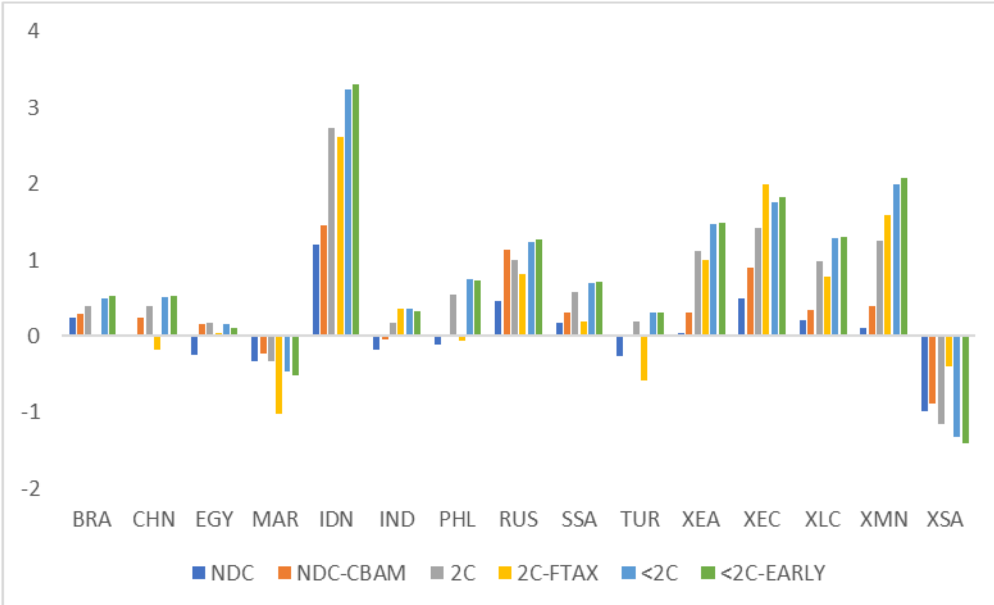

Figure 18. Percent changes in the GVC participation in electronics relative to the baseline scenario in 2050 across low- and middle-income countries/regions.

Notes: Changes in GVC participation for each country/region are measured as a percent difference from the corresponding level under the baseline scenario. Description of country/regional labels is available in the Annex B.

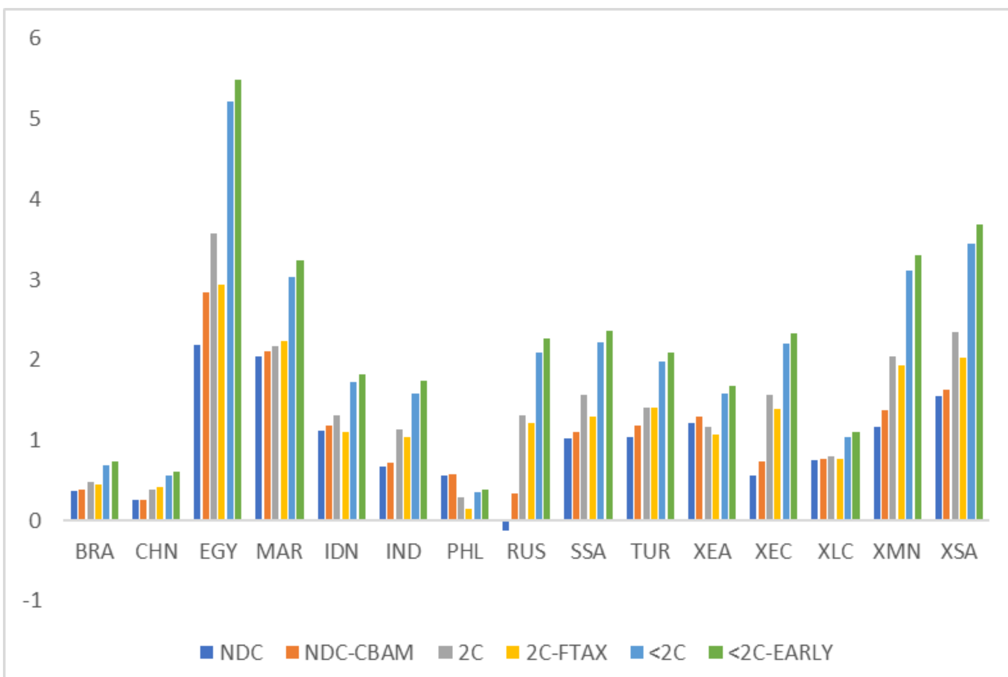

Figure 19. Percent changes in the GVC participation in transport services relative to the baseline scenario in 2050 across low- and middle-income countries/regions.

Notes: Changes in GVC participation for each country/region are measured as a percent difference from the corresponding level under the baseline scenario. Description of country/regional labels is available in the Annex B.

4. Country profiles

This section discusses selected country-specific results in terms of implications for sectoral trade. Four country-cases are featured: Brazil, China, Egypt and India, illustrating the reallocation of trade under the most ambitious mitigation scenario. They show how globally, low carbon-intensive sectors replace high carbon-intensive sectors, with the differences in impacts stemming from varying production processes (cost structures), changing demand patterns, and the resulting shifts in relative competitiveness across sectors and countries.

4.1. Egypt

Climate mitigation policies offer Egypt the opportunity to diversify away from dependence on fossil fuels and chemicals. Although the sector coverage is quite broad, the CGE model offers a tool to inform countries on the challenges and opportunities for exports in a world with climate mitigation policies. For Egypt, global climate mitigation efforts offer an opportunity to expand sectors such as transport services, other services, and textiles, and to diversify away from emissions intensive sectors, which account for more than one third of total exports. Among low emissions intensive exports, Egypt is expected to be a competitive exporter of transport services, other services, food and agriculture, and textiles products. With global climate mitigation policies, Egypt's exports of fossil fuels and chemicals as a share of total exports decline by 5.1 and 2.2 percentage points, respectively, under the "<2C early" scenario compared to the baseline (see Figure 20). Overall, in 2050, the share of exports of low emissions intensive sectors increases by 6.9 percentage points under the "<2C early" scenario.

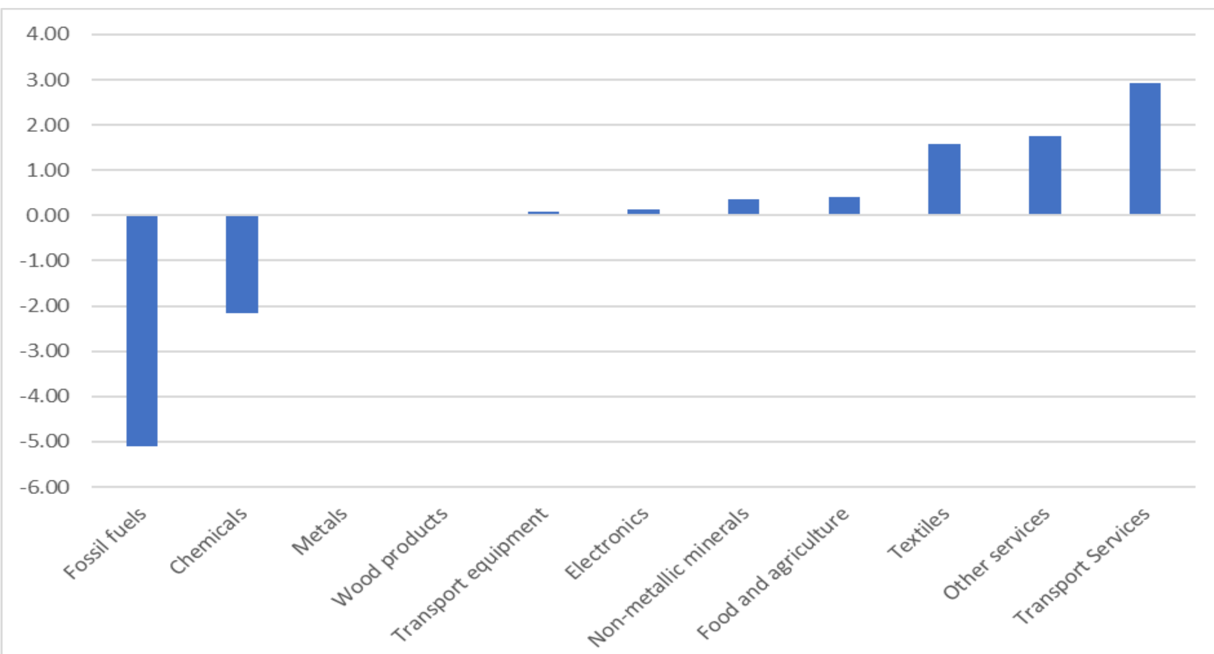

Figure 20. Egypt exports, change in sectoral export composition in 2050 under the "<2c early" scenario, relative to the baseline

Notes: Results are reported in changes in percentage points. Change in sectoral export composition refers to sectoral exports as a share of total exports in 2050 under the "<2C early" scenario, relative to the baseline

Given the current structure of exports, Egypt has been unable to exploit the benefits of GVC participation in sophisticated sectors. The changing composition of global exports with climate mitigation offers an opportunity for countries such as Egypt to participate more fully in GVCs. The opportunities for integration into GVCs for Egypt are greatest in services sectors, in particular transport services. At the same time, climate change mitigation efforts lead to a decrease in GVC participation in Egypt's fossil fuels and emissions intensive manufacturing sectors, in particular the chemicals sector. The magnitude of declines increases with the growing ambition of mitigation efforts.

4.2. China

China's exports of electronics and transport equipment decline with climate mitigation policies. China is a competitive exporter of low emissions intensive manufacturing products. Electronics and textiles were the top two export sectors for China in 2014, accounting for 46.5 percent and 15.3 percent of total Chinese exports to the world. Meanwhile, exports of energy-intensive and trade-exposed (EITE) sectors accounted for just 15.7 percent of total exports in 2014; of that, chemicals accounted for 7.9 percent and metals for 4.4 percent. Mitigation efforts change China's trade structure, with the share of electronics and transportation equipment sectors declining by 0.6 percentage points and 0.3 percentage points, respectively, under the "<2C early" scenario compared to the baseline. On the other hand, the shares of chemicals, transport services and textiles rise (Figure 21). The export sectors that decline in importance have higher emissions intensity than competitor countries. For example, China's production of electronics is more energy-intensive compared with other economies (it is twice as high as that of the United States.) With the mitigation effort, China's electronics exports become relatively less competitive on the international market. Overall, low emissions intensive exports as a share of total Chinese exports decline slightly under the "<2C early" scenario. GVC participation increases the most in transport services and chemicals**.**

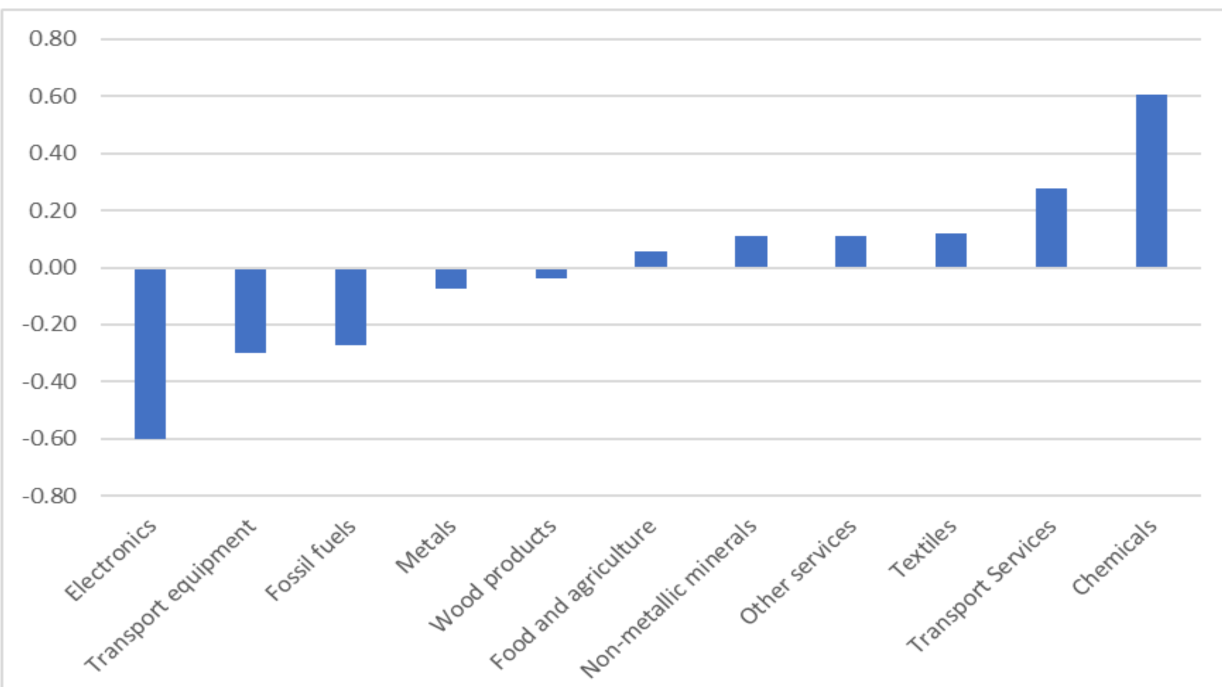

Figure 21. Change in the sectoral composition of Chinese exports in 2050 under the "<2c early" scenario, relative to the baseline

Notes: Results are reported in changes in percentage points. Change in sectoral export composition refers to sectoral exports as a share of total exports in 2050 under the "<2c early" scenario, relative to the baseline.

4.3. Brazil

Brazil has an opportunity to shift away from exports of food and agricultural products and fossil fuels, while implementing domestic decarbonization efforts. Brazil has a comparative advantage in exporting food and agricultural as well as wood products[4]. Food and agricultural and services exports were the top export sectors for Brazil in 2014, accounting for 44.6 percent and 10.8 percent of total Brazilian exports in 2014, respectively. EITE sectors exports accounted for 23.2 percent of the total in 2014; of that, fossil fuels accounted for 9.5 percent and metals for 6.9 percent. Mitigation efforts result in a relative increase in exports of services, chemicals, and textile products (Figure 23) and a decline in fossil fuels and food and agriculture. GVC participation in Brazil increases the most in the food and agriculture as well as transport services sectors, and the participation rate rises as the climate change mitigation effort grows. Only in fossil fuels does Brazil's GVC participation decline. GVC participation in Brazil increases the most in the food and agriculture as well as transport services sectors.

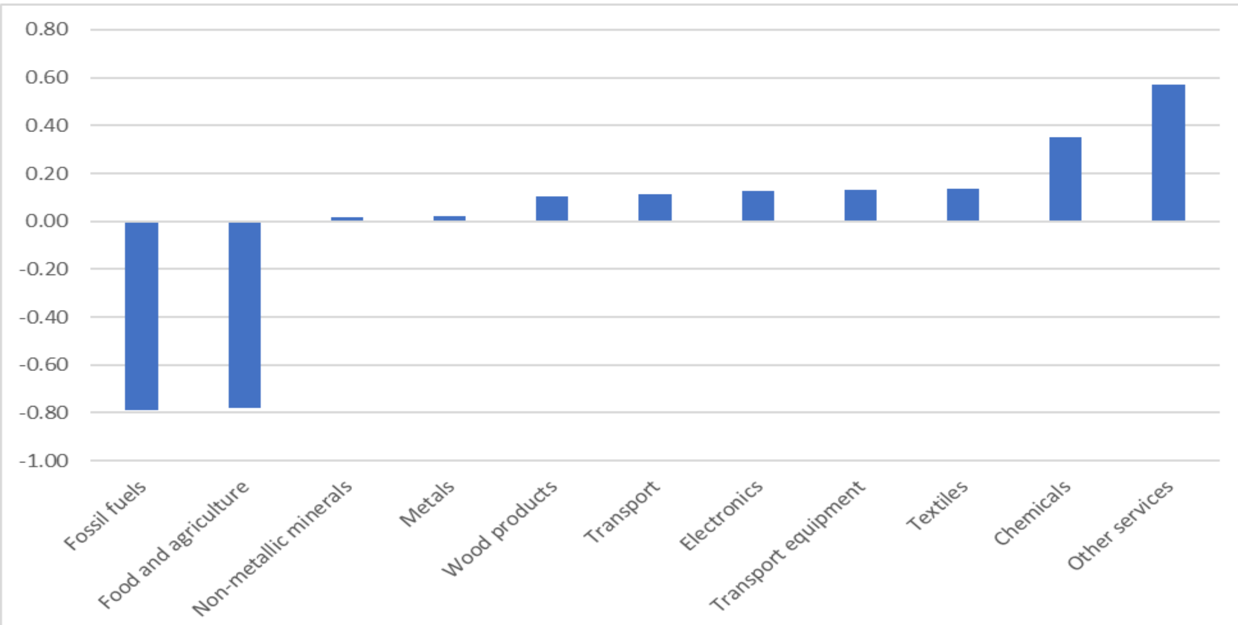

Figure 22. Brazilian exports, change in sectoral export composition in 2050 under the "<2c early" scenario, relative to the baseline

Notes: Results are reported in changes in percentage points. Change in sectoral export composition refers to sectoral exports as a share of total exports in 2050 under the "<2c early" scenario, relative to the baseline.

4.4. India

Climate change mitigation efforts lead to a change in India's trade structure, with exports of other services and transport services becoming relatively more important. On the other hand, the shares of transport equipment, electronics, fossil fuels and EITE products decline (Figure 23). The CO_2 emission intensities of India's transport equipment and electronic exports are higher than in competitor economies, making Indian exports relatively less competitive on the international market. GVC participation in India's transport services sector increase the most.

[4] It should be noted that the results of the simulations presented here do not incorporate the potential impact of anti-deforestation policies imposed by the EU.

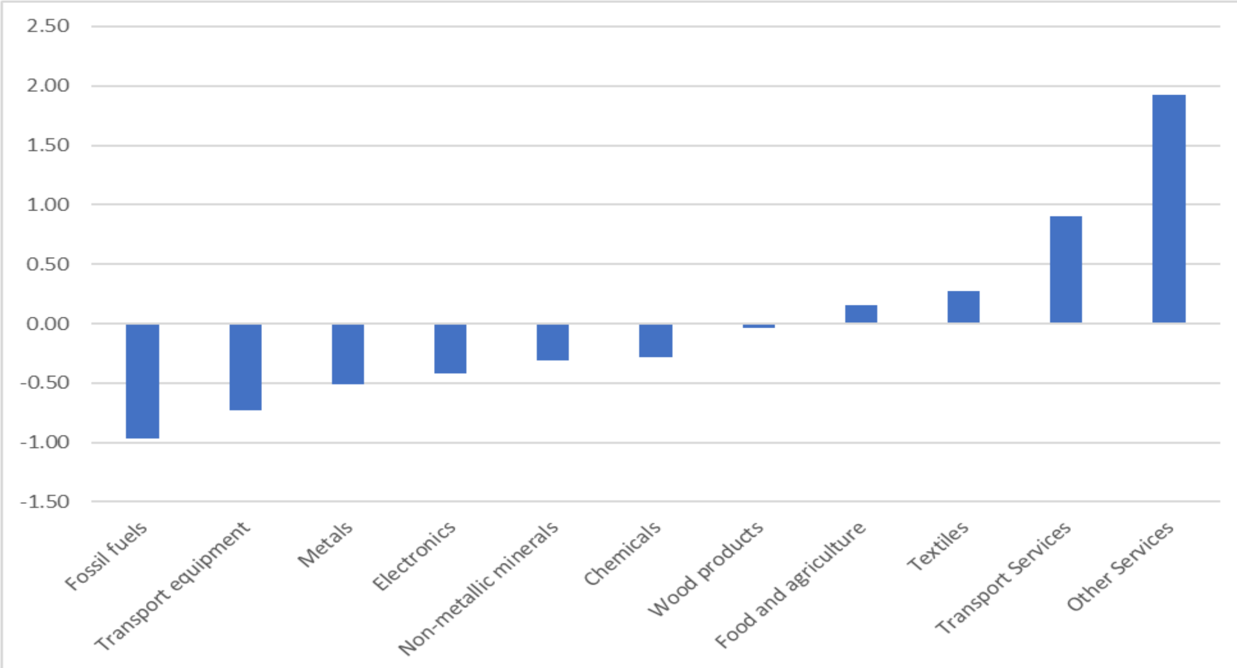

Figure 23. Indian exports, change in sectoral export composition in 2050 under the "<2c early" scenario, relative to the baseline

Notes: Results are reported in changes in percentage points. Change in sectoral export composition refers to sectoral exports as a share of total exports in 2050 under the "<2c early" scenario, relative to the baseline**.**

5. A Comparison with Earlier Studies

The World Trade Organization's 2022 report on climate change and international trade (WTO, 2022) also uses a CGE model to analyze how climate change mitigation efforts affect the international trade patterns. The main results from the WTO report are similar to ours, though sectoral results differ somewhat. The simulation results from both the WTO report and our paper suggest that the global share of fossil fuel exports in total energy exports would decline. Moreover, both studies suggest that knowledge-based sophisticated sectors (or low carbon intensive sectors), such as electronics and transportation equipment, will gain their share in exports. Our paper offers more detailed sectoral results, indicating that the extent to which low carbon intensive sectors gain their share in exports depends largely upon the carbon revenue recycling approach — when carbon revenue is used to reduce factor taxes in low-carbon activities, including services, light manufacturing and renewable energy, one can observe that clean sectors, like electronics and transport equipment, gain substantially larger shares in exports compared to scenarios where carbon revenue is recycled via direct payments to households.

The WTO report also finds that the climate change mitigate effort shifts countries' production and comparative advantage from fossil fuel sectors to energy-intensive industrial sectors, such as iron and steel. Such result is not found in our paper. It is worth pointing out that the CGE model used in the WTO 2022 report and the CGE model used in our paper adopts different macroeconomic closures — the ENVISAGE model used in our analysis fixes the trade balance in real terms for each country, while the WTO Global Trade Model (GTM) adopts the rate of return (RORE) closure, that is, regional savings are aggregated into the global supply of savings, which are invested across regions until percentage changes in expected regional rates of returns (RORE) on capital are equalized. The trade balance is therefore endogenous in the RORE closure. Moreover, the simulation scenarios also differ — while both the WTO 2022 report and our analysis assumes having regional emission reduction requirements for 2030 according to NDC targets, the WTO 2022 report explicitly assumes additional policies and measures beyond carbon-pricing post-2030 (e.g. an explicit phase-out of coal, additional cost-free energy efficiency improvements, etc.). In our modeling approach all mitigation efforts are costed in and represented via carbon prices.

Vrontisi et al. (2020) used a global CGE model GEM-E3 exploring regional and sectoral trade impacts of the climate mitigation scenarios focusing on the G20 economies but also reporting the global results. In their 2C-consistent scenario authors find that the global GDP declines by around 1.1% in 2030 and 2.1% in 2050, which is somewhat higher than the estimates provided here – a reduction in GDP between 0.5% and 1.4% across the range of 2C-consistent scenarios (Annex J). Vrontisi et al. (2020) report a decline in the total volumes of trade by 6.2% in 2050, while we find a reduction of 3.2%-5.4% across the range of 2C-compatible scenarios. Thus, both Vrontisi et al (2020) and our estimates are consistent in terms of suggesting a decline in the trade-to-GDP ratio globally under the implementation of 2C-consistent climate mitigation scenarios. Consistent with the results reported here, Vrontisi et al. (2020) also suggest that the most substantial expansion in the economic activity at the sectoral level is observed for the case of clean energy technologies. Authors also find that USA, Europe and several other high-income countries gain comparative advantage in clean energy technologies exports, expending their market share at the cost of China and India. We find similar result in terms of regional competitiveness for the case of low-carbon sectors such as electronics. Though it should be noted that both studies rely on the GTAP Data Base and thus the obtained results are partly driven by the comparative advantages captured in the data for the reference year.

6. Summary and Conclusions

Using a combination of the ENVISAGE computable general equilibrium and the TIAM global energy system models this study analyzes the economic impacts of different global climate change mitigation scenarios, this paper finds that the cost of putting the global economy on the low carbon transition pathways is manageable – even under the most ambitious “<2C-EARLY” scenario, a global GDP declines by only 1.4% in 2050 relative to baseline, which, if translated to the annual growth rate, corresponds to a slow down of around 0.05% per year. Less ambitious climate change mitigation scenarios result in an even lower decline in global GDP. Meanwhile, the simulation results also show that recycling carbon revenue in a form of reduced factor taxes will lead to a lower overall economic cost of transition, as well as a lower carbon price needed to achieve the specified mitigation target.

When it comes to the economic impact on international trade, simulation results demonstrate that implementing climate mitigation scenarios results in a decline in demand for fossil fuels and increasing costs of energy and energy-intensive intermediate inputs. Increasing production costs lead to a decline in total exports for all countries, with low- and middle-income countries experiencing a higher magnitude of export reduction (1.6%-6.9% across scenarios). Meanwhile, the share of fossil fuels in total exports and imports falls across all climate mitigation scenarios.

The country-level impacts of the mitigation policies on trade shows that for the NDC-CBAM scenario in particular, some energy-intensive sectors that face the CBAM, such as chemicals, in some cases face even bigger decline in trade than fossil fuels. Under the NDC-CBAM scenario, there is also an increasing share of exports of some energy-intensive goods and services due to carbon leakage: for instance, most developing countries show an increasing share of exports of transport services under the "NDC-CBAM" scenario.

The simulation results also demonstrate that the extent to which low carbon intensive sectors gain their share in exports largely depends on the carbon revenue recycling approach. When the carbon revenue is used to reduce factor taxes in low-carbon activities, one can observe that low carbon intensive sectors, such as electronics and transport equipment, gain substantially larger shares compared to the scenario where carbon revenue is recycled via direct payments to households. Moreover, carbon revenue recycling via reduced carbon taxes also limits an overall magnitude of adverse trade implications, as production costs for selected sectors are being reduced.

Though non-energy intensive sectors, such as electronics and transportation equipment, gain their shares in global exports with a growing mitigation effort, global exports (in absolute volume terms) of non-energy intensive products, such as electronics, transportation equipment, rice, and construction services, still experience a small decline with a growing mitigation effort. The decline is driven mainly by 1) countries who are relatively more energy-intensive in producing such products compared to their competitors; 2) countries who are relatively more energy-intensive in producing such products compared to the average emission intensity for all products in that country. Some developing countries and regions expand their production and exports in some non-energy intensive agricultural sectors with a growing mitigation effort — for instance, India increases its production and exports of rice products and the SSA region expands their exports in grains and oil seeds. The reason is mainly because the agricultural sectors in these developing countries are either less energy-intensive compared to their advanced economy counterparts, or less energy-intensive compared to the average emission intensity for all products in that country.

Finally, when it comes to GVC participation rate, the simulation results show that GVC participation in the low-carbon intensive sectors increase with a growing ambition of mitigation efforts, while GVC participation rate for the energy-intensive sectors, most notably the fossil fuels sector, decline with a growing mitigation effort. Individual countries results show that the GVC participation of transport activities and electronics increase the most among developing countries.

Individual country-level results also show that climate change mitigation efforts result in a changing trade structure, with countries moving away from exporting in energy intensive sectors and shifting into exporting more in non-energy intensive sectors. Sectors where individual countries shift into exporting more are often clean sectors that these countries have a comparative advantage in exporting in 2014 (measured by the relative comparative advantage – RCA). For instance, in the case of Egypt, with the climate mitigation efforts, the country moves away from exporting in energy intensive sectors, such as fossil fuels and chemicals, and moves into exporting more in services and textiles, the sectors where Egypt has a comparative advantage in exporting in 2014. The sectoral-level CO_2 emission intensity also affects the changing trade structure. For instance, although China has an export strength in its electronics sector (as measured by the RCA), Chinese electronics exports as the share of total Chinese exports decline under the "<2C early" scenario compared to the baseline. This is happening because China's electronics manufacturing is more emission-intensive compared to some other countries. With the climate mitigation policies, China's electronics exports become relatively less competitive on the international market.

While in the current study we attempted to provide quantification of the potential implications of ambitious mitigation policies on global value chains, providing some broad insights, there are several important improvements and extensions that could further advance the analyzes presented here. *First,* in terms of a more refined representation of the climate policy scenarios and the energy transition, one might consider a more comprehensive link between the energy system and CGE models with a better alignment of the technological parametrization and energy mixes across the two frameworks. *Second,* in the part the policy representation, in the current study we used carbon pricing as a single representative instrument. However, in many country cases, governments are implementing a variety of different policies and measures, including subsidies, to specific technologies and products, emission standards, phasing out of the fossil fuels subsidies, etc. Implementing these country-specific policy instruments would help to provide a more realistic representation of the future impacts of the mitigation policies on GVCs. *Third,* the analysis presented here would benefit from a more detailed representation of selected products and related value chains. The latter could include both upstream commodities, such as critical minerals (copper, nickel, cobalt, lithium, etc.), as well as downstream sectors that supply key intermediate inputs for the low-carbon transition – solar panels, wind turbines and batteries. In addition, a representation of the alternative production technologies for selected energy-intensive and trade-exposed sectors could be relevant, e.g. primary and secondary production of plastic, metals, paper, etc. The latter would allow to explicitly capture the potential transition toward circularity principles within the mitigation scenarios. *Finally,* future research would benefit from better exploring the role of trade in supporting the low-carbon transition. While results reported here and in the earlier literature suggest that trade, especially in selected commodities, could be impacted rather substantially within the ambitious mitigation scenarios, not enough attention has been paid to understanding the role of trade in lowering the energy transition costs – both from the point of view of supporting commodity and service exchanges across countries exploiting their competitive advantages, as well as through the potential technological transfers and spillovers.

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Annex A. Description of the TIAM model technological structure

1. Primary energy: Each region has a 21-step supply curve, with the base quantity as INDPROD. Base prices, step sizes and elasticities are assumptions tuned to roughly mimic the IEA price trajectories. The energy forms used are hard coal, brown coal, coking coal, crude oil, Natural Gas, Industrial and municipal waste, biogas.
2. Transformation sector: includes Refineries, Coke ovens, blast furnace, transfers, coal to liquids, and gas blending.
3. Power: Existing stock is built from Platts database and efficiencies are adjusted to calibrate to the IEA balances. Country-level renewable electricity potential comes from NREL and EIA. Electricity supply and demand can be modelled at a flexible number of seasonal and diurnal timeslices. This makes the model particularly strong to explore high variable renewable scenarios.
4. Hydrogen: Production of hydrogen is included using all available technologies. Hydrogen production can be coupled with the intermittent electricity production. Hydrogen demand is generated by native technologies and blending in natural gas distribution systems.
5. CCS: The structure for CCS options exists with details at a regional level and various types of potential for storing CO2.
6. Trade: The model includes global markets for coal, oil, LNG, and biofuels, and existing bilateral links for electricity and natural gas.
7. Industry: 9 energy intensive sub-sectors are modelled, each with up to 9 energy services that are produced by explicit technologies.
8. Transportation: 8 segments in road transport with detailed technology choices. Rail, aviation, and shipping are treated in a generic manner – controlled fuel substitution in response to fuel prices or emission constraints.
9. Buildings: Residential and commercial sector energy use is split into space heating, space cooling, hot water, cooking, lighting, and other uses (appliances). Each end-use is supplied by technologies with different efficiencies, fuels, and costs.
10. Agriculture: this sector is modeled in a generic way without technology detail. Controlled endogenous fuel switching is allowed

Annex B. Regional aggregation of ENVISAGE

No.	Region	GTAP concordance
1	United States (USA)	United States of America (USA)
2	China (CHN)	China (CHN)
3	Russian Federation (RUS)	Russian Federation (RUS)
4	India (IND)	India (IND)
5	Turkey (TUR)	Turkey (TUR)
6	Brazil (BRA)	Brazil (BRA)
7	Indonesia (IDN)	Indonesia (IDN)
8	Philippines (PHL)	Philippines (PHL)
9	Egypt (EGY)	Egypt (EGY)
10	Morocco (MAR)	Morocco (MAR)
11	EU-27	Austria (AUT), Belgium (BEL), Cyprus (CYP), Denmark (DNK), Finland (FIN), France (FRA), Germany (DEU), Greece (GRC), Ireland (IRL), Italy (ITA), Luxembourg (LUX), Malta (MLT), Netherlands (NLD), Portugal (PRT), Spain (ESP), Sweden (SWE), Czech Republic (CZE), Estonia (EST), Hungary (HUN), Latvia (LVA), Lithuania (LTU), Poland (POL), Slovakia (SVK), Slovenia (SVN), Bulgaria (BGR), Croatia (HRV), Romania (ROU)
12	Rest of East Asia and Pacific (XEA)	Mongolia (MNG), Rest of East Asia (XEA), Brunei Darussalam (BRN), Malaysia (MYS), Thailand (THA), Viet Nam (VNM), Rest of Oceania (XOC), Cambodia (KHM), Laos (LAO), Rest of Southeast Asia (XSE)
13	Rest of South Asia (XSA)	Bangladesh (BGD), Nepal (NPL), Rest of South Asia (XSA), Pakistan (PAK), Sri Lanka (LKA)
14	Rest of ECA (XEC)	Albania (ALB), Belarus (BLR), Ukraine (UKR), Rest of Eastern Europe (XEE), Rest of Europe (XER), Kazakhstan (KAZ), Kyrgyzstan (KGZ), Tajikistan (TJK), Rest of Former Soviet Union (XSU), Armenia (ARM), Azerbaijan (AZE), Georgia (GEO)
15	Rest of Middle East and North Africa (XMN)	Bahrain (BHR), Iran (IRN), Israel (ISR), Jordan (JOR), Kuwait (KWT), Oman (OMN), Qatar (QAT), Saudi Arabia (SAU), United Arab Emirates (ARE), Rest of Western Asia (XWS), Tunisia (TUN), Rest of North Africa (XNF)
16	Rest of Sub-Saharan Africa (SSA)	Benin (BEN), Burkina Faso (BFA), Guinea (GIN), Senegal (SEN), Togo (TGO), Rest of Western Africa (XWF), Central Africa (XCF), South-Central Africa (XAC), Ethiopia (ETH), Madagascar (MDG), Malawi (MWI), Mauritius (MUS), Mozambique (MOZ), Rwanda (RWA), Tanzania (TZA), Uganda (UGA), Zambia (ZMB), Rest of Eastern Africa (XEC), Rest of South African Customs Union (XSC), Cameroon (CMR), Côte d'Ivoire (CIV), Ghana (GHA), Nigeria (NGA), Kenya (KEN), Zimbabwe (ZWE), Botswana (BWA), Namibia (NAM), South Africa (ZAF)
17	Rest of Latin America and Caribbean (XLC)	Mexico (MEX), Rest of North America (XNA), Argentina (ARG), Bolivia (BOL), Chile (CHL), Colombia (COL), Ecuador (ECU), Paraguay (PRY), Peru (PER), Uruguay (URY), Venezuela (VEN), Costa Rica (CRI), Guatemala (GTM), Honduras (HND), Nicaragua (NIC), Panama (PAN), El Salvador (SLV), Rest of Central America (XCA), Rest of South America (XSM), Dominican Republic (DOM), Jamaica (JAM), Puerto Rico (PRI), Trinidad and Tobago (TTO), Rest of Caribbean (XCB)
18	High income Asia (HYA)	Hong Kong (HKG), Japan (JPN), Korea (KOR), Taiwan (TWN), Singapore (SGP)
19	Rest of high-income (XHY)	United Kingdom (GBR), Switzerland (CHE), Norway (NOR), Rest of EFTA (XEF), Australia (AUS), New Zealand (NZL), Canada (CAN), Rest of the World (XTW)

Annex C. Sectoral aggregation of ENVISAGE

No.	Sector code	Sector description	GTAP-Power 10 sectors
1.	ric	Paddy rice and processed rice	pdr, pcr,
2.	xgr	Other grains and oil seeds	wht, gro, osd
3.	xcr	Other crops	v_f, c_b, pfb, ocr, sgr
4.	ctl	Cattle and dairy	ctl, rmk, wol
5.	xlv	Other livestock	oap
6.	coa	Coal	coa
7.	oil	Oil	oil
8.	gas	Gas	gas, gdt
9.	frs	Forestry	frs
10.	nrs	Natural resource products	oxt
11.	pmt	Processed meat	cmt, omt
12.	dry	Dairy products	mil
13.	xfd	Other processed foods	fsh, vol, ofd, b_t
14.	wdp	Wood, paper and lumber products	lum, ppp
15.	twp	Textile, wearing apparel and leather products	tex, wap, lea
16.	p_c	Refined oil	p_c
17.	chm	Chemical products (incl. rubber and plastics)	bph, chm, rpp
18.	nmm	Non-metallic minerals	nmm
19.	met	Metals	i_s, nfm
20.	meq	Fabricated metal goods, vehicles and transport equipment	fmp, mvh, otn, omf
21.	elq	Electronics and electrical equipment	ele, eeq, ome
22.	etd	Electricity transmission and distribution	TnD
23.	nuc	Nuclear electricity	NuclearBL
24.	clp	Coal-fired electricity	CoalBL
25.	gsp	Gas-fired electricity	GasBL, GasP
26.	olp	Oil-fired electricity	OilBL, OilP
27.	hyd	Hydro-electricity	HydroBL, HydroP
28.	sol	Solar electricity	SolarP
29.	wnd	Wind electricity	WindBL
30.	xel	Other renewable electricity	OtherBL
31.	cns	Construction	cns
32.	trd	Trade including warehousing	trd, afs, whs
33.	wtp	Water transport	wtp
34.	atp	Air transport	atp
35.	otp	Other transport	otp
36.	xsv	Other Services	wtr, cmn, ofi, ins, rsa, obs, ros, osg, edu, hht, dwe

Notes: full list of the GTAP 10 Data Base sectors is available at https://www.gtap.agecon.purdue.edu/databases/v10/v10_sectors.aspx#Sector65. GTAP-Power 10 Data Base sectors are listed in Chepeliev (2020).

Annex D. Selected baseline assumptions for the ENVISAGE model

Assumption	Implementation	Specific assumptions
Costs of renewables are declining over time	The cost reduction is implemented using a hyperbolic specification with a cost asymptote. The curve is calibrated to three parameters—the asymptote (relative to current costs), a targeted reduction and the year the target is reached.	Wind and solar—the asymptote is 60% of today's price and the costs are dropping by 30% between 2014 and 2050. Other renewables—the asymptote is 70% and the costs are dropping by 20% between 2014 and 2050.
Non-price related changes in preferences towards renewables	Preference 'twist' parameters change the preference for one set of commodities in a demand system relative to other commodities, but without changing the aggregate cost (Dixon and Rimmer, 2002; van der Mensbrugghe, 2019).	We assume a target for renewable electricity as a share of total electricity demand and implement the twist assuming no change in prices (from the base year). The assumed shares are provided in Appendix D. The actual shares are likely to be higher given the decline in costs and the developments in the cost of other power activities. We do not introduce renewables, as a new technology, in case of countries with "0" renewables share in the benchmark 2014 year.
Target increase in electricity share for agents (trend towards electrification)		We assume that electricity consumption shares (in total energy consumption) increase two times by 2050 for all agents except transportation. For the case of air transport we assume a three times increase, for the case of road and water transport a four times increase. We also assume that the electrification rate in road transportation reaches at least 30 percent in 2050 and water transportation at least 10 percent. For households we assume a three times increase in electrification rates. An upper bound of 95% share of electricity in total energy use is set across all agents.
Energy efficiency improvements	Improvements in energy efficiency are captured by the autonomous energy efficiency improvement parameter (AEEI). We assume AEEI to be differentiated by countries, energy commodities and agents.	AEEIs vary between 1.5 and 3.0 percent across countries, with an exception of China with 3.5 percent. AEEIs are set to "0" in transformation activities and fossil fuel-based generation except gas power, where a 0.5 percent value is used. For energy intensive sectors (chemicals, metals and non-metallic minerals) a value of 1 percent is used, except China, where a 2 percent value is applied. AEEIs are assume to be higher in developing countries with a more rapid GDP growth and lower in the advanced economies. Overall, considering heterogeneous AEEI assumptions across countries, energy commodities and agents weighted average AEEIs range between around 1.0 and 2.0 percent.
Improvements in international transport costs		Costs decline by one percent per annum.
Increasing share of services		A trend toward increasing demand for services as intermediate inputs is incorporated within the baseline scenario – a 'servitization' assumption.

Annex E. Assumed shares of renewables in electricity generation under the baseline scenario, percent

Region	Targeted share
United States (USA)	40
European Union (E27)	45
Rest of Europe and Central Asia (XEC)	25
Turkey (TUR)	25
High income Asia (HYA)	25
Rest of high income countries (XHY)	30
China (CHN)	35
Russia (RUS)	30
Egypt (EGY)	20
Morocco (MAR)	30
Rest of Middle East and North Africa (XMN)	20
Rest of East Asia (XEA)	25
Indonesia (IDN)	25
Philippines (PHL)	25
India (IND)	25
Rest of South Asia (XSA)	25
Brazil (BRA)	25
Rest of Latin America and Caribbean (XLC)	25
Sub-Saharan Africa (SSA)	25

Notes: Renewables under targeting include, wind, solar and other renewable generation.

Annex F. Carbon price trajectories assumed under the baseline scenario, 2014 USD per tCO2

Year\region	EU-27	China	Rest of high-income countries
2021	33.6	7.5	33.6
2022	37.3	8.6	37.3
2023	40.9	9.5	40.9
2024	44.6	10.5	44.6
2025	48.2	11.6	48.2
2026	51.9	12.9	51.9
2027	55.5	14.3	55.5
2028	59.2	15.8	59.2
2029	62.8	17.5	62.8
2030	66.4	19.3	66.4
2031	68.4	19.9	68.4
2032	70.5	20.5	70.5
2033	72.6	21.1	72.6
2034	74.8	21.8	74.8
2035	77	22.4	77
2036	79.3	23.1	79.3
2037	81.7	23.8	81.7
2038	84.2	24.5	84.2
2039	86.7	25.2	86.7
2040	89.3	26	89.3
2041	92	26.7	92
2042	94.7	27.6	94.7
2043	97.6	28.4	97.6
2044	100.5	29.2	100.5
2045	103.5	30.1	103.5
2046	106.6	31	106.6
2047	109.8	31.9	109.8
2048	113.1	32.9	113.1
2049	116.5	33.9	116.5
2050	120	34.9	120

Notes: In the baseline scenario carbon prices are imposed on a selected set of energy-intensive sectors. The latter include chemicals, metals, non-metallic minerals, petroleum products, wood products and electricity generation.

Annex G. Carbon price trajectories assumed under the NDC scenario, 2014 USD per tCO2

Country\year	2024	2027	2030	2035	2040	2045	2050
China	10.5	15.2	21.0	30.0	38.3	48.9	62.4
Indonesia	1.3	3.2	4.9	30.0	38.3	48.9	62.4
Philippines	4.3	9.7	15.4	30.0	38.3	48.9	62.4
Rest of EAP	4.5	10.5	16.3	30.0	38.3	48.9	62.4
India	1.8	4.3	6.7	30.0	38.3	48.9	62.4
Rest of South Asia	2.4	5.5	8.2	30.0	38.3	48.9	62.4
Russia	1.9	4.1	6.2	30.0	38.3	48.9	62.4
Turkey	2.1	4.9	7.6	30.0	38.3	48.9	62.4
Rest of ECA	2.7	6.9	11.1	30.0	38.3	48.9	62.4
Egypt	2.5	5.6	8.1	30.0	38.3	48.9	62.4
Morocco	2.7	6.2	9.6	30.0	38.3	48.9	62.4
Rest of MENA	5.6	13.0	19.2	30.0	38.3	48.9	62.4
Rest of SSA	1.1	2.5	3.7	30.0	38.3	48.9	62.4
Brazil	12.7	26.4	43.1	55.1	70.3	89.7	114.5
Rest of LAC	3.8	9.2	14.3	30.0	38.3	48.9	62.4
High-income Asia	9.2	25.0	42.2	53.9	68.8	87.8	112.1
EU-27	42.4	75.4	137.5	159.4	184.7	214.2	248.3
United States	4.4	10.9	17.2	30.0	38.3	48.9	62.4
Rest of high-income	39.7	64.3	92.1	117.6	150.1	191.6	244.5

Notes: In the baseline scenario carbon prices are imposed on all emitting agents, including households.

Annex H. Carbon price trajectories assumed under the “<2C” and “<2C EARLY” Scenarios, 2014 USD per tCO2

Country/Year	2024	2027	2030	2035	2040	2045	2050
“<2C” Scenario							
CHN	10.5	15.2	21.0	159.4	215.3	290.7	392.5
IDN	1.3	3.2	4.9	159.4	215.3	290.7	392.5
PHL	4.3	9.8	15.4	159.4	215.3	290.7	392.5
XEA	4.5	10.5	16.3	159.4	215.3	290.7	392.5
IND	1.8	4.3	6.7	159.4	215.3	290.7	392.5
XSA	2.4	5.5	8.2	159.4	215.3	290.7	392.5
RUS	1.9	4.1	6.2	159.4	215.3	290.7	392.5
TUR	2.1	4.9	7.6	159.4	215.3	290.7	392.5
XEC	2.7	6.9	11.1	159.4	215.3	290.7	392.5
EGY	2.5	5.6	8.1	159.4	215.3	290.7	392.5
MAR	2.7	6.2	9.6	159.4	215.3	290.7	392.5
XMN	5.6	13.0	19.2	159.4	215.3	290.7	392.5
SSA	1.1	2.5	3.7	159.4	215.3	290.7	392.5
BRA	12.7	26.4	43.2	159.4	215.3	290.7	392.5
XLC	3.7	9.2	14.3	159.4	215.3	290.7	392.5
HYA	9.2	25.0	42.2	159.4	215.3	290.7	392.5
E27	42.4	75.4	137.5	159.4	215.3	290.7	392.5
USA	4.4	10.9	17.2	159.4	215.3	290.7	392.5
XHY	39.7	64.3	92.2	159.4	215.3	290.7	392.5

2024	2027	2030	2035	2040	2045	2050
“<2C Early” Scenario (same carbon price trajectory for all countries/regions)						
43.4	82.9	162.3	211.9	276.6	360.9	471.1

Annex I. Additional results from the TIAM model

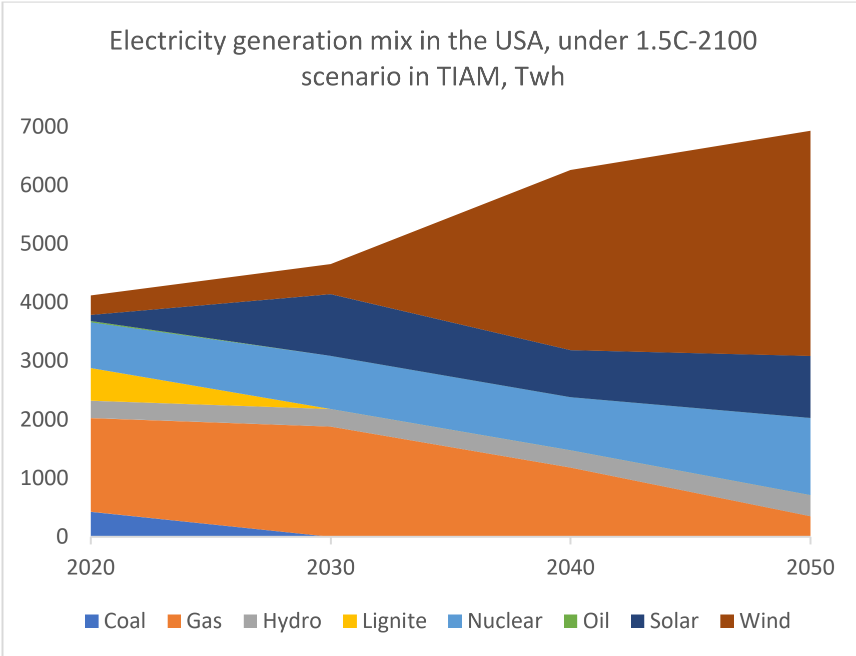

Figure I.1: Electricity generation mix in the USA in the TIAM model under the 1.5C-2100 scenario, TWh

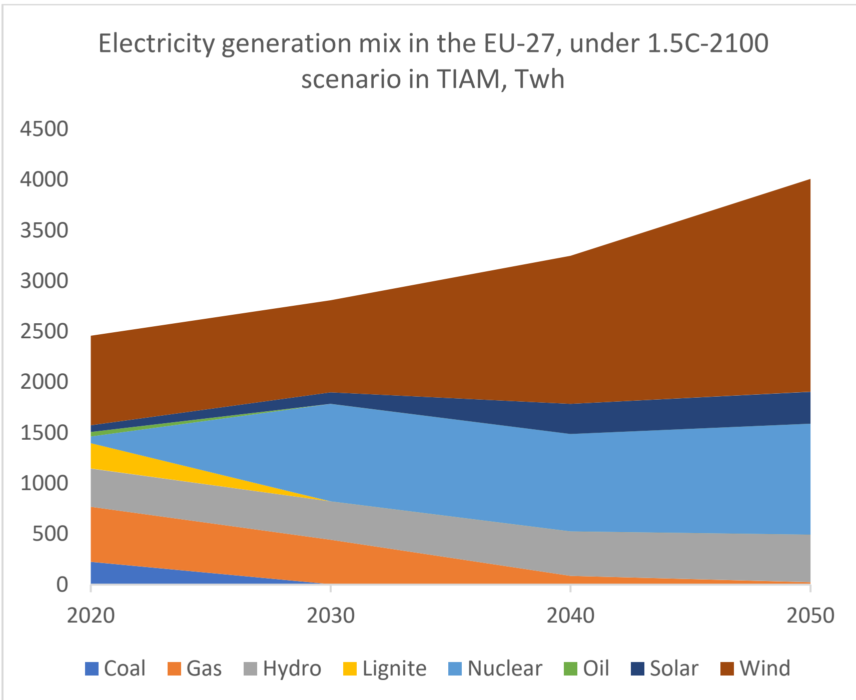

Figure I.2: Electricity generation mix in the EU-27 in the TIAM model under the 1.5C-2100 scenario, TWh

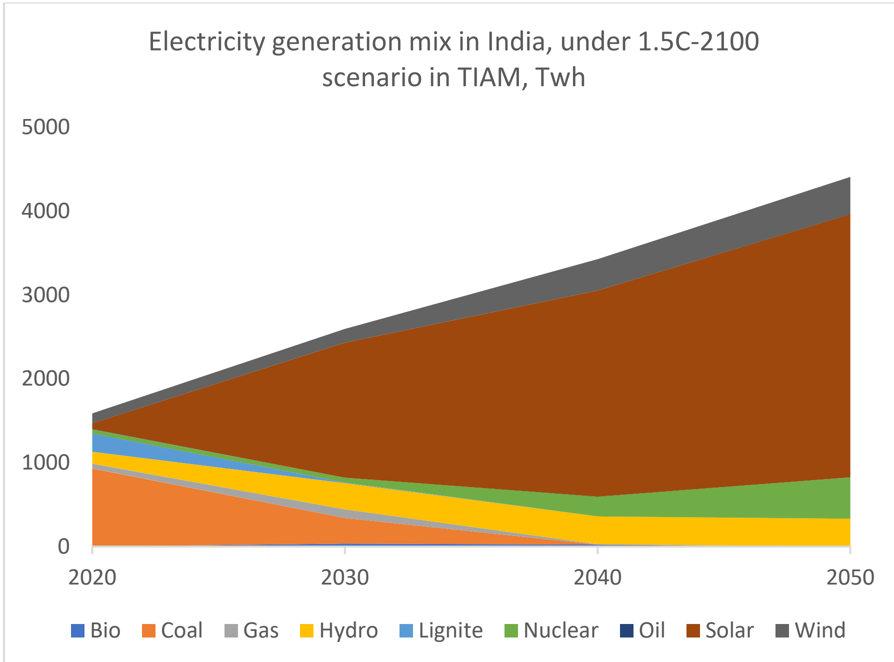

Figure I.3: Electricity generation mix in India in the TIAM model under the 1.5C-2100 scenario, TWh

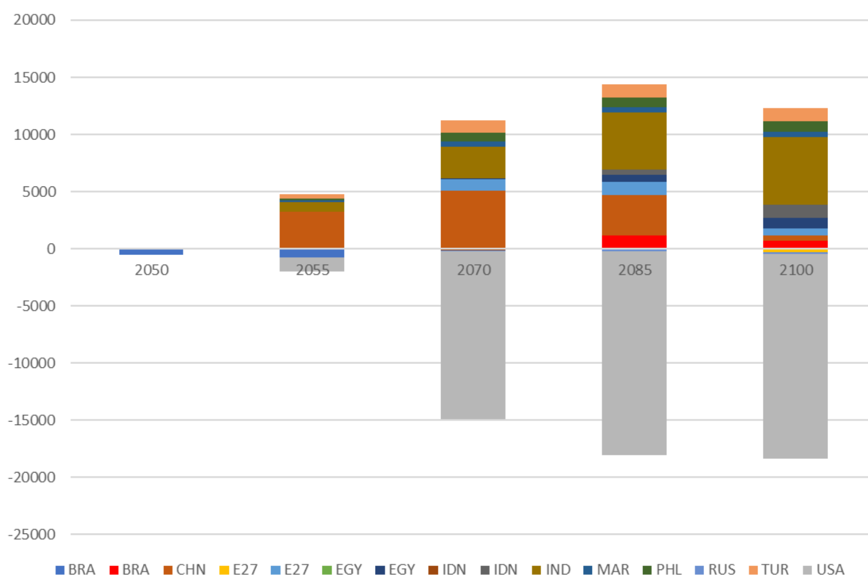

Figure I.4: Change in hydrogen trade in the TIAM model across countries/regions, under the 1.5C-2100 scenario, in petajoule (PJ). Negative numbers refer to net exports and positive numbers refer to net imports.

Annex J. Changes in real GDP and welfare across countries/regions and scenarios, % w.r.t. baseline in 2050

Table J.1. Changes in real GDP, % w.r.t. baseline in 2050

Region\scenario	NDC	NDC-CBAM	2C	2C-FTAX	<2C	<2C-EARLY
United States	-0.6%	-0.6%	-1.7%	-1.7%	-2.0%	-2.3%
China	-0.4%	-0.4%	-0.9%	-0.7%	-1.0%	-1.6%
Russian Federation	-0.2%	-1.2%	-0.2%	0.7%	-0.4%	-0.7%
India	-1.2%	-1.2%	-2.6%	-1.2%	-2.9%	-4.2%
Turkey	0.1%	0.2%	0.3%	0.9%	0.3%	0.1%
Brazil	0.0%	0.0%	-0.3%	0.0%	-0.3%	-0.4%
Indonesia	-0.2%	-0.2%	-0.7%	0.7%	-0.9%	-1.1%
Philippines	-0.7%	-0.7%	-1.7%	-1.0%	-1.9%	-2.2%
Egypt	-0.7%	-0.6%	-1.3%	-0.9%	-1.6%	-1.5%
Morocco	-0.4%	-0.4%	-1.4%	-1.0%	-1.7%	-2.3%
EU-27	-0.6%	-0.7%	-0.5%	-0.2%	-0.7%	-0.7%
Rest of East Asia and Pacific	-0.5%	-0.6%	-1.6%	-1.4%	-2.0%	-2.4%
Rest of South Asia	-0.5%	-0.5%	-0.8%	-0.3%	-0.9%	-1.1%
Rest of ECA	-2.6%	-2.5%	-5.6%	-5.5%	-6.4%	-6.8%
Rest of Middle East and North Africa	0.3%	0.0%	2.0%	3.5%	2.1%	1.9%
Rest of Sub-Saharan Africa	-0.4%	-0.4%	-0.9%	-0.1%	-1.0%	-1.1%
Rest of Latin America and Caribbean	-0.1%	-0.1%	-0.5%	-0.1%	-0.7%	-0.9%
High income Asia	-0.3%	-0.3%	-0.5%	-0.2%	-0.6%	-0.7%
Rest of high-income	-0.5%	-0.5%	-0.5%	-0.4%	-0.7%	-0.8%
Low and middle income, excl. China	*-0.4%*	*-0.5%*	*-0.9%*	*0.0%*	*-1.1%*	*-1.5%*
Low and middle income (all)	*-0.4%*	*-0.5%*	*-0.9%*	*-0.3%*	*-1.0%*	*-1.5%*
High income	*-0.5%*	*-0.6%*	*-0.9%*	*-0.8%*	*-1.2%*	*-1.3%*
World	**-0.5%**	**-0.5%**	**-0.9%**	**-0.5%**	**-1.1%**	**-1.4%**

Table J.1. Changes in welfare, % w.r.t. baseline in 2050

Region\scenario	NDC	NDC-CBAM	2C	2C-FTAX	<2C	<2C-EARLY
United States	-0.6%	-0.6%	-1.2%	-1.2%	-1.4%	-1.6%
China	-0.4%	-0.5%	-0.6%	-0.6%	-0.6%	-0.9%
Russian Federation	-0.3%	-2.0%	0.4%	1.5%	0.3%	0.2%
India	-0.8%	-0.8%	-1.2%	-0.8%	-1.2%	-1.8%
Turkey	0.6%	0.5%	2.0%	2.4%	2.4%	2.4%
Brazil	0.1%	0.1%	0.0%	0.1%	0.0%	0.0%
Indonesia	-0.3%	-0.4%	-0.5%	-0.3%	-0.6%	-0.8%
Philippines	-0.9%	-0.9%	-1.8%	-1.8%	-2.1%	-2.3%
Egypt	-0.9%	-1.0%	-1.2%	-0.9%	-1.5%	-1.4%
Morocco	-0.1%	-0.1%	0.2%	0.4%	0.3%	0.2%
EU-27	0.1%	0.1%	0.1%	0.2%	0.0%	0.0%
Rest of East Asia and Pacific	-0.5%	-0.6%	-0.7%	-1.4%	-0.8%	-1.0%
Rest of South Asia	-0.7%	-0.7%	-0.6%	-0.6%	-0.7%	-0.8%
Rest of ECA	-3.6%	-3.8%	-6.3%	-6.7%	-6.8%	-7.0%
Rest of Middle East and North Africa	-0.5%	-1.0%	4.1%	5.5%	4.9%	4.6%
Rest of Sub-Saharan Africa	-0.8%	-0.8%	-1.2%	-0.7%	-1.4%	-1.6%
Rest of Latin America and Caribbean	-0.1%	-0.1%	-0.2%	0.0%	-0.4%	-0.5%
High income Asia	-0.3%	-0.3%	-0.4%	-0.5%	-0.3%	-0.3%
Rest of high-income	-0.5%	-0.4%	-0.7%	-0.5%	-0.8%	-0.9%
Low and middle income, excl. China	-0.5%	-0.8%	-0.3%	0.1%	-0.3%	-0.5%
Low and middle income (all)	-0.5%	-0.6%	-0.4%	-0.2%	-0.4%	-0.7%
High income	-0.3%	-0.3%	-0.7%	-0.6%	-0.8%	-0.9%
World	**-0.4%**	**-0.5%**	**-0.5%**	**-0.4%**	**-0.6%**	**-0.8%**