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Greening Global Trade: How Climate Policies Reshape Comparative Advantage of Developing Countries

by Maksym Chepeliev (GTAP/Purdue University),[1] Maryla Maliszewska (World Bank), Amit Kanudia (KanORS), Wen Jin Yuan (USITC), Channing Arndt (GTAP/Purdue University), Dominique van der Mensbrugghe (GTAP/Purdue University)

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Center for Global Trade Analysis
Department of Agricultural Economics
Purdue University

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Center for Global Trade Analysis
Department of Agricultural Economics
Purdue University
West Lafayette, IN 47907
https://www.gtap.agecon.purdue.edu

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Abstract

This paper uses a combination of the global energy system model KINESYS and global computable general equilibrium (CGE) model ENVISAGE to analyze the impact of future climate mitigation policies. Results are subsequently linked to an atmospheric source-receptor model. Principal findings are as follows: (i) Holding global temperatures below 2^{o}C requires significant policy effort. A uniformly applied tax of nearly $400 (2014 USD) per tonne of CO2eq is required. (ii) Ignoring benefits and co-benefits of mitigation policy, the cost to the global economy is relatively small. Holding global temperature rise below 2^{o}C implies a loss of about 1.1% of global GDP. Using the revenue from carbon taxation to offset distorting taxes, as opposed to transferring carbon revenues in a lump sum manner to households, further reduces or reverses economic losses. (iii) However, benefits and co-benefits are significant. Benefits relate to reduced climate-related damages, such as lower frequency/intensity of extreme weather events. The co-benefit in focus relates to reduced air pollution. The monetized co-benefits of reduced air pollution substantially exceed the costs of mitigation alone by 2050 in most scenarios. Low-income countries experience a higher benefit-to-cost ratio compared to high-income economies. (iv) As mitigation effort increases, global trade-to-GDP ratios decline. Mitigation substitutes strongly traded fossil fuels for mostly domestically generated electricity. This downdraft on trade volume is a major and robust result. (v) The composition of trade shifts in logical ways, with production/trade in energy-intensive products tending to decline more and production/trade in less energy-intensive products tending to decline less.

[1] Corresponding author. Email: mchepeli@purdue.edu
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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^{o}C relative to pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5^{o}C (UNFCCC, 2015). Even to stay within a rise of 2^{o}C relative to pre-industrial levels will require significant efforts (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, including 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 food systems to be less emissions intensive (particularly of methane) through changes behavioral patterns (Marteau et al., 2021) such as dietary shifts toward less meat-oriented food systems (Clark et al., 2020; Theurl et al., 2020) and/or changes in food production technologies; and major infrastructural upgrades in many cases requiring an early retirement of the existing fossil fuel -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 a largely unexplored area.

Principal findings are as follows.

1. Holding global temperatures below 2^{o}C requires significant policy effort. A uniformly applied tax of nearly $400 (2014 USD) per tonne of CO2eq is required.
2. Ignoring benefits and co-benefits of mitigation policy, the cost to the global economy is relatively small. Holding global temperature rise below 2^{o}C implies a loss of about 1.1% of global GDP. Using the revenue from carbon taxation to offset distorting taxes, as opposed to transferring carbon revenues in a lump sum manner to households, further reduces or reverses economic losses.

3. However, benefits and co-benefits are significant. Benefits relate to reduced climate-related damages, such as lower frequency/intensity of extreme weather events.[3] The co-benefit in focus relates to reduced air pollution. The monetized co-benefit of reduced air pollution substantially exceeds the costs of mitigation alone by 2050 in most scenarios. Low-income countries experience a higher benefit-to-cost ratio compared to high-income economies.
4. As mitigation effort increases, global trade-to-GDP ratios decline. Mitigation substitutes strongly traded fossil fuels for mostly domestically generated electricity. This downdraft on trade volume is a major and robust result.
5. The composition of trade shifts in logical ways, with production/trade in energy-intensive products tending to decline more and production/trade in less energy-intensive products tending to decline less.

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. Section 3 presents results. Section 4 compares results with existing literature, and Section 5 concludes and highlights priority areas for future research.

2. Methodology and scenarios

To comprehensively explore the impacts of future mitigation policies, we rely on a multi-model assessment framework, which includes the Knowledge-based Investigation of Energy System Scenarios (KINESYS), a global computable general equilibrium (CGE) model ENVISAGE, and an atmospheric source-receptor model TM5-FASST.

Using this set of modelling tools, we analyze a suite of exploratory climate mitigation scenarios. Our scenario framework, first, includes 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 2ºC, as well as stylized 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. KINESYS energy system model

KINESYS is a multi-region inter-temporal partial equilibrium model of the global energy system (Kanudia, 2023). 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

[3] The range of estimated benefits is very large (Morris et al, 2025).

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. The KINESYS 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 KINESYS model. Regional aggregation of the KINESYS model used in the current study is consistent with the regional aggregation of the ENVISAGE modelling framework discussed below. The KINESYS 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, 2024).[4] 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 (2024).

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). The 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 and across regions. 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. First, the KINESYS 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 2°C and 1.5°C within the 2070 and 2100 timeframe. As a result, we obtain 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

[4] Initial development of the model was undertaken at the World Bank.

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 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 (servicification) and reduction in international transportation costs.[5] 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 the 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[6] 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

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[5] 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.

[6] https://climateactiontracker.org/

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 a stylized carbon border adjustment mechanism (CBAM) implemented by the European Union. Emission scope and sectoral coverage of the CBAM is expanding over time.
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^{o}C.
4.	2C-FTAX	"2C" scenario with carbon revenue recycling via reduction of 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^{o}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^{o}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 the 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 the 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 stylized 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. Given that the data set deployed in this study doesn't allow for the detailed disaggregation of CBAM products and that our simulations assume expansion of CBAM scope and coverage over time, which has not been clearly defined by the EU yet, the results of this scenario should be treated with caution, as a potential upper bound of the impacts of CBAM.

"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 CO_2. It should be noted that within all analyzed scenarios, the carbon prices are imposed on CO_2 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 CO_2 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 the KINESYS 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 KINESYS

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

Figures 1 and 2 provide an overview of the emission trajectories and carbon budgets across the applied modelling frameworks and scenarios within the 2019-2050 timeframe.

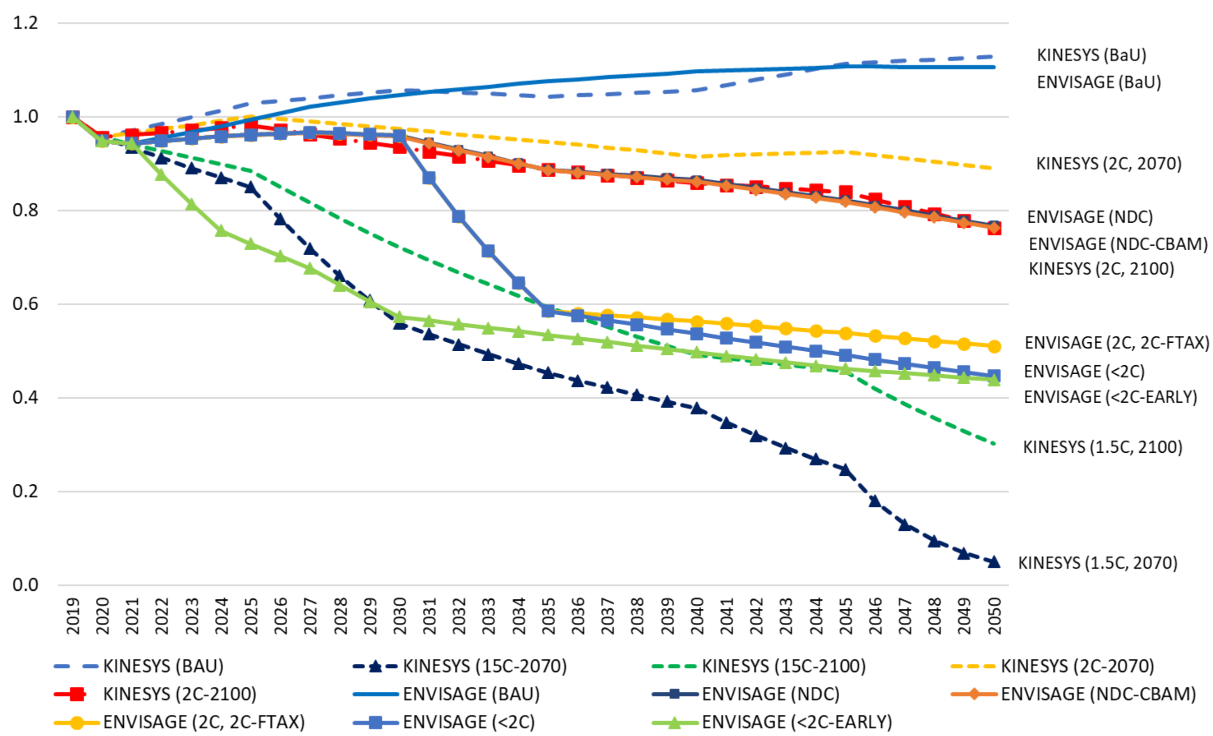

Figure 1. Emission trajectories in KINESYS and ENVISAGE, 2019=1

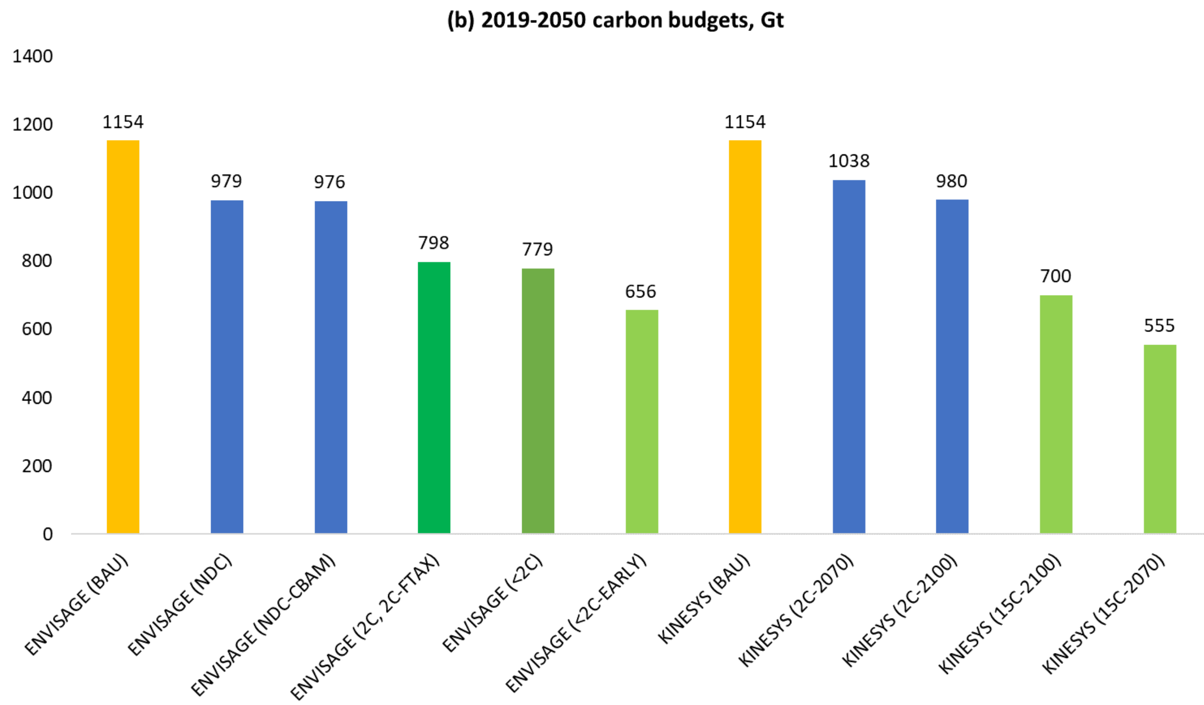

Figure 2. Carbon budgets across scenarios and models, Gt (2019-2050 cumulative)

3. Key findings

3.1. Required policy and investment efforts are large

The policy and investment efforts required to put the global economy on the low carbon transition pathway are substantial (Pahle et al., 2018; Keohan and Victor, 2016). To achieve the emissions targets in the “2C” and “2C-EARLY” would require CO2eq tax levels of about $393 and $471 (measured in 2014 USD) per tonne respectively (see Annex H). This level of taxation drives transformation in the global energy system. The magnitude and rapidity of change vary across mitigation scenarios. The common key element in all scenarios is a switch to carbon-free electricity generation principally from solar, wind, nuclear, hydro and other renewable energy sources from fossil-based electricity. This electricity generation transformation is combined with substitution of direct fossil fuel use by electricity in transport, industry, and heating/cooling of buildings. For instance, motor vehicles production moves away from internal combustion cars and toward electric vehicles (EVs).

To support these transformations, 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. These complex value chains are not explicitly disaggregated in the ENVISAGE modelling framework; however, an overall magnitude of the anticipated changes can be discerned from the observed transformations within the electricity generation activity via the KINESYS model.

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 3a). 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 3b). 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 for even more dramatic transformations in supply chains, as the output of solar power grows by over 180-210 times across scenarios.

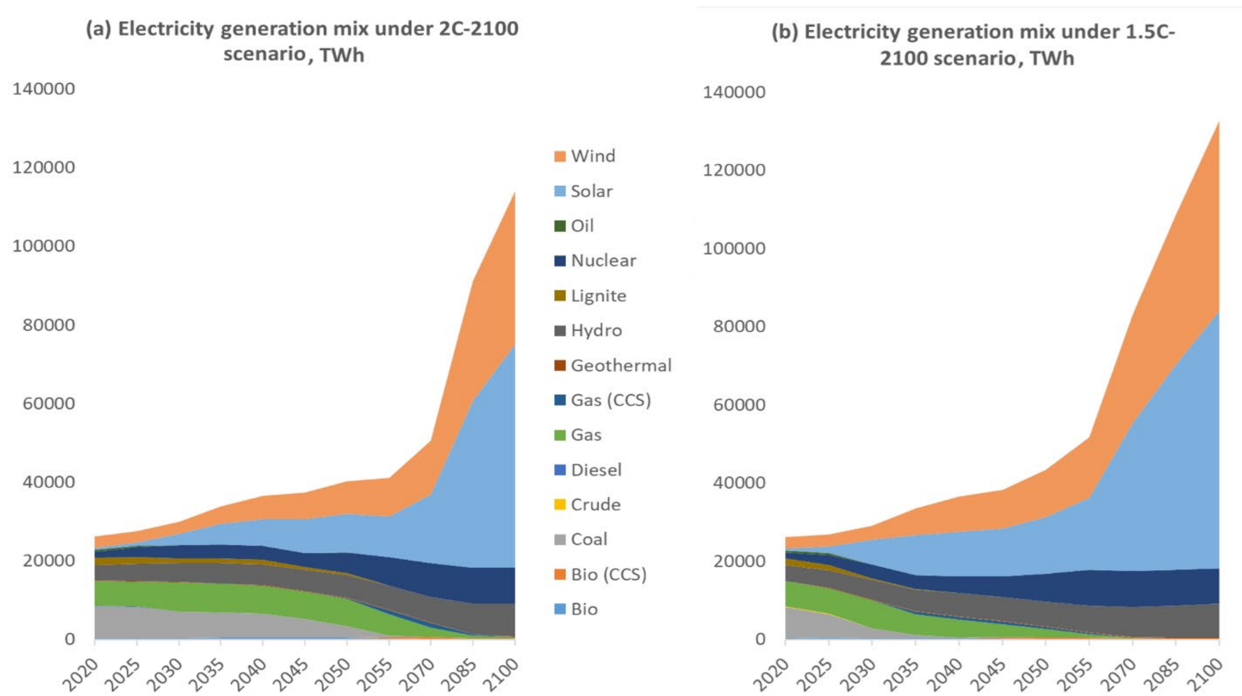

Figure 3. Global electricity generation mix in the KINESYS model under 2C-2100 (a) and 1.5C-2100 (b) scenarios, TWh

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 3). Our modeling results suggest that if unconstrained by political decisions, nuclear power generation in the EU could expand substantially between 2020 and 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 also 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 significantly 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. Costs are low and co-benefits large

Over the past decade or so, the cost of solar and wind power generation—and of battery storage—has fallen at an extraordinary pace. The global levelized cost of electricity (LCOE) for utility-scale solar PV has dropped roughly 80–90% since about 2010, while onshore wind has declined about 40–60% as turbines became larger, more efficient, and cheaper to manufacture (Lazard 2023; IRENA 2023). Battery costs have fallen even more dramatically, with lithium-ion pack prices down roughly 85–95% from the early 2010s to the early 2020s, sliding from about $1,000 per kilowatt-hour to around $100–150 per kWh (Argonne National Laboratories 2025). These cost declines imply a relatively inexpensive transition.

Ignoring co-benefits, the cost of transition to a very low emissions economies would be rather moderate. Figure 4 reports macroeconomic indicators by scenario and country income category. 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%. Associated welfare losses are even lower than the estimated reductions in GDP and range between 0.4% and 0.8%. 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.

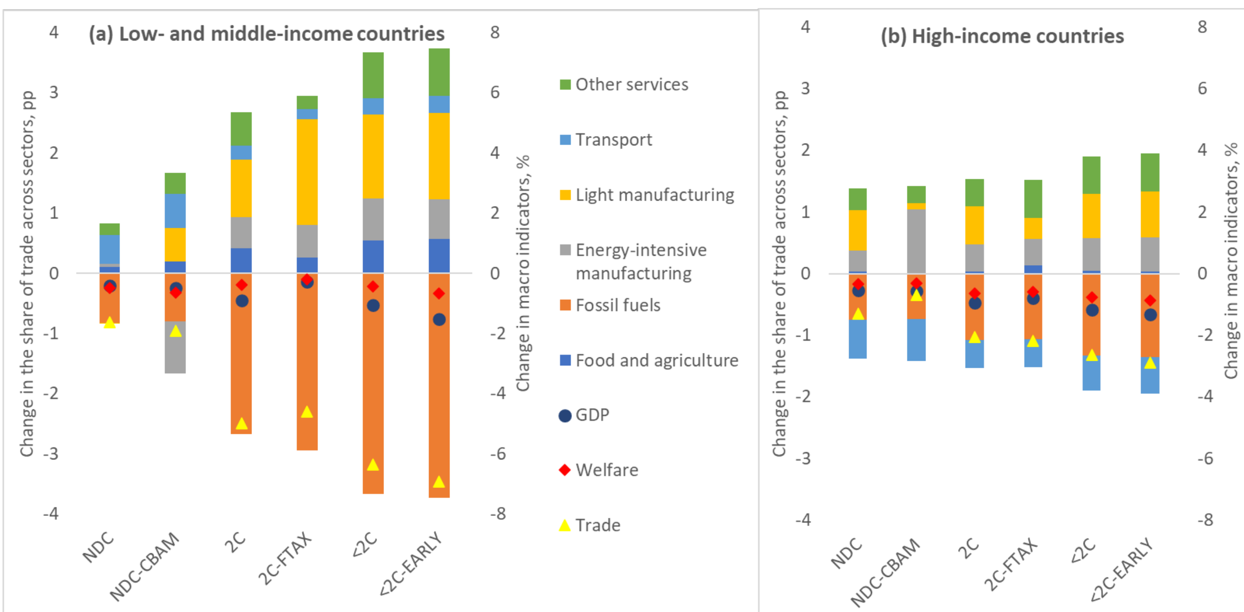

Figure 4. Key macro indicators and percentage point changes in global sectoral export shares across scenarios and country groups relative to the baseline scenario in 2050.

Notes: Percent changes in macro indicators (GDP, welfare and trade) are reported on the right vertical axis. Percentage point changes in the share of sectoral exports in total exports are measured relative to the baseline scenario and reported 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.

The carbon taxes imposed to drive the transition generate significant revenue. Consistent with earlier literature (e.g. Freire-González and Ho, 2019; Chen et al., 2020), recycling carbon revenue in the form of reduced factor taxes, as opposed to the direct lump-sum payments, decreases the overall economic costs of transition and reduces the carbon prices needed to achieve the defined mitigation targets. As can be seen from the comparison of "2C" and "2C-FTAX" scenarios in Annex I, carbon revenue recycling via reduced factor taxes on low-carbon activities, including services, light manufacturing and renewable energy, reduces the mitigation costs by almost a factor of two – 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. The factor tax recycling option, in fact, could even lead to net welfare-improving outcomes for this group of countries (Table J.2, Annex J).

As noted, 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 come on top of the reduced climate-related damages such as lowered frequency and magnitude of catastrophic weather events (Ornes, 2018; Tol, 2018). None of these benefits (or avoided costs) are accounted for in the current modeling framework. 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 a 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 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 5). 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 5). "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).

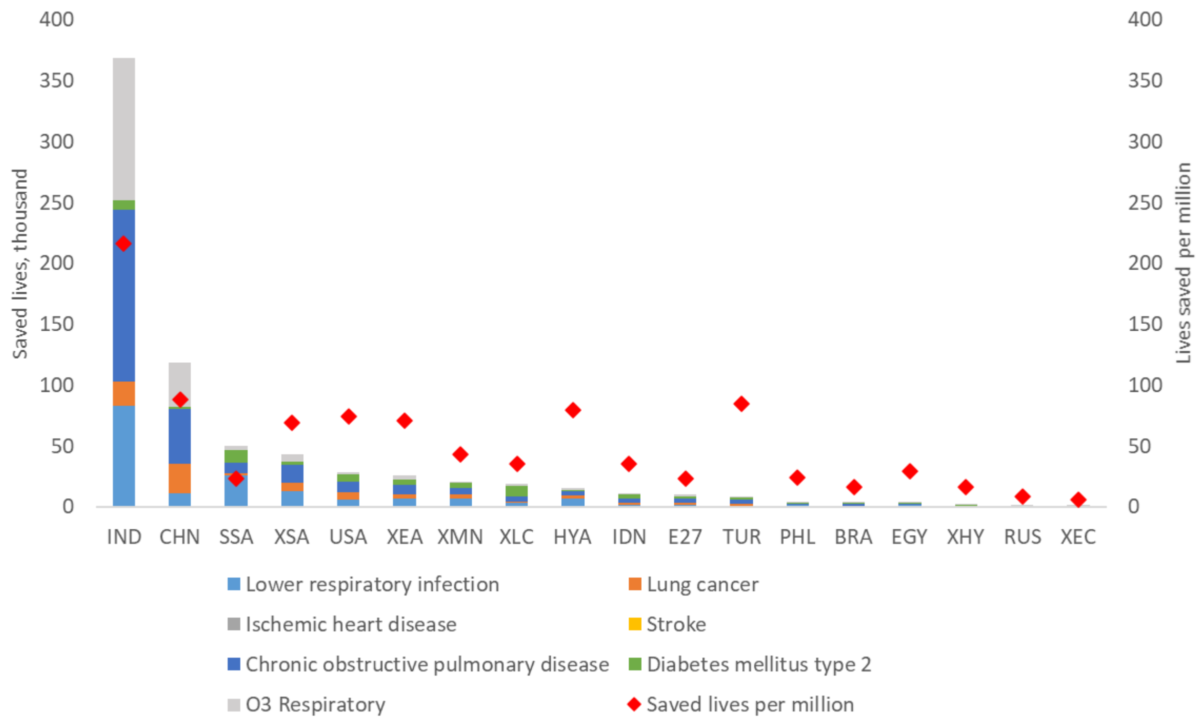

Figure 5. Mortality reductions due to improved air quality under 2C scenario in 2050
Notes: Regional labels are identified in Annex B.

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 6). A larger ratio 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 6). 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. It 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.

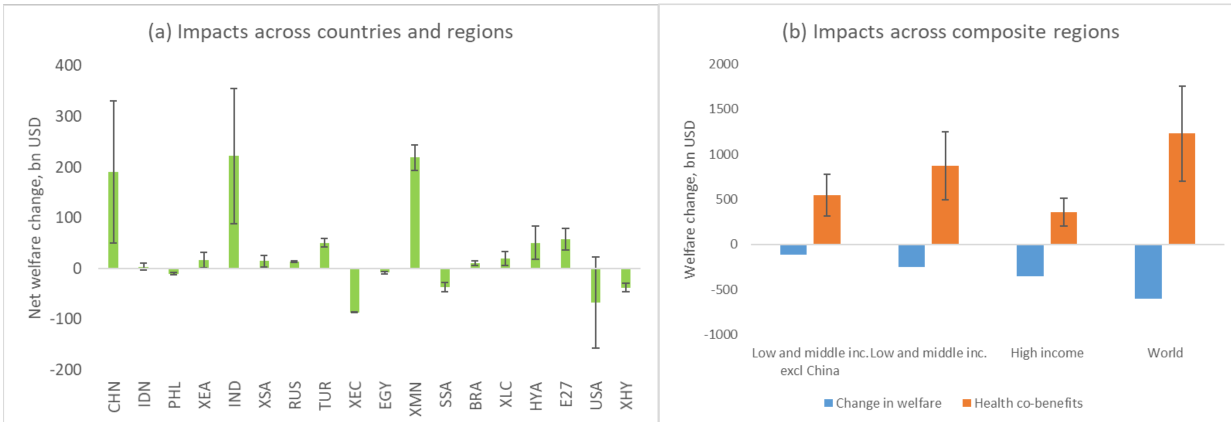

Figure 6. Health co-benefits and mitigation costs under 2C scenario in 2050, billion USD

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. Regional labels are identified in Annex B.

3.3. Trade-to-GDP ratios decline

A principal macroeconomic result is a decline in aggregate trade. Figure 4 shows significant declines in trade for every class of economy and across all scenarios. For example, in the "2C" scenario, exports by low-/middle-income and high-income economies drop by about 5% and 2% respectively (relative to baseline). The decline in low- and middle-income economies is larger because the share of fossil fuels in trade is larger. In Figure 7, which shows changes in trade under the 2C scenario in 2050, aggregate trade drops in every low- and middle-income region and by an important amount. As noted, this is not a new result, but it is large and robust and provides the context around which other results must be interpreted.

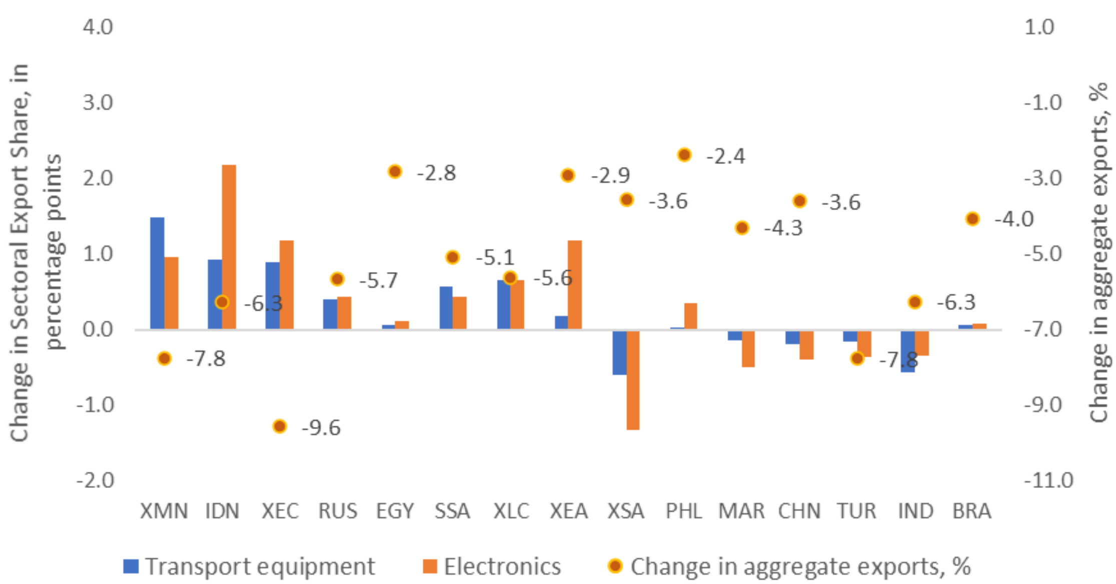

Figure 7. Changes in aggregate exports across low- and middle-income countries and regions, under the "2C" scenario relative to baseline in 2050

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. Regional labels are identified in Annex B.

The story behind this significant decline in trade-to-GDP ratios goes as follows. Due to quirks of geology, fossil fuel extraction is strongly concentrated in specific geographies. Because fossil fuels are (currently) a *sine qua non* for economic activity, fossil fuels are strongly traded. Most countries in the world are structural fossil fuel importers. These countries are obliged to export very significant volumes of goods and services to import fossil fuels. As noted, the energy transition involves generating electricity via wind, solar, nuclear, hydro, and geothermal and electrification of industry, transport, and heating/cooling of buildings. These replacement technologies for fossil fuels tend not to be strongly traded, especially over long distances. Hence, in the model, technical change and policy are pushing fossil fuels out of the system and replacing them with (mainly) domestically produced energy (via wind, solar, nuclear, etc.). For structural importers, a key net movement in factors of production associated with mitigation at scale is from exporting sectors to domestic energy production, substantially diminishing fuel imports and the non-fuel exports that were necessary to finance the imports.

The flip side is structural oil exporters. The energy transition reduces the value of their fossil fuel natural resource endowments and lowers export volumes. Structural fossil fuel exporters become less wealthy, and the decline in fossil fuel production/trade compromises their ability to import. To afford imports, fossil fuel exporters must shift factors of production from fossil fuel and non-tradeable production to non-fossil fuel exports (a major structural adjustment). But, they are not capable of fully offsetting the decline in fossil fuel export real value. In short, both structural importers and structural exporters reduce trade volumes.

A second robust and driving result in the model is a rise in the relative price of energy (Table 3). This rise is not large relative to the standard deviation in prices in fossil fuel markets; nevertheless, it favors relative expansion of the services sector on a global basis due to its particularly low energy intensity. This sector also tends to be large in GDP and lightly traded relative to output. The relative expansion of a large and lightly traded sector is another mechanism tending to drive down aggregate trade. While present, this driver is far less important than the volume changes driven by the energy transition.

Table 3: Change in global energy prices by scenarios, % w.r.t. baseline

	NDC	**NDC-CBAM**	**2C**	**2C-FTAX**	**<2C**	**<2C-EARLY**
2024	3.3%	3.3%	3.3%	3.3%	3.3%	20.6%
2027	7.3%	7.3%	7.3%	7.1%	7.3%	29.9%
2030	10.4%	10.5%	10.4%	10.0%	10.4%	37.5%
2035	15.4%	15.5%	32.8%	29.0%	32.8%	35.9%
2040	16.4%	16.9%	30.5%	26.4%	31.8%	34.2%
2045	17.5%	18.0%	28.2%	23.9%	30.6%	32.7%
2050	18.2%	18.7%	26.0%	21.7%	29.0%	30.0%

Within this context of an overall reduction in the volumes of trade, variation across scenarios, products, and countries is observed. For example, in the case of "NDC-CBAM" scenario and with a focus on the relatively near-term (2030), the overall magnitude of trade implications is lower than under other more ambitious mitigation efforts; however, energy-intensive sectors that face the CBAM, such as chemicals, in some cases face even more adverse impacts than fossil fuels (Figure 8). The 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.

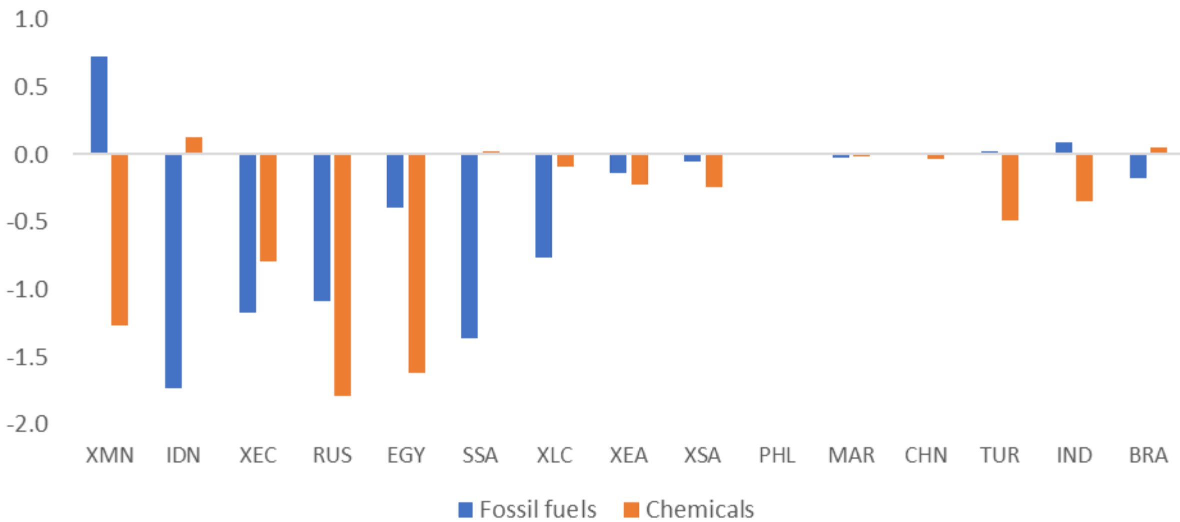

Figure 8. Changes in fossil fuel and chemical sectoral export shares across low- and middle-income countries, under the "NDC-CBAM" scenario, in 2030 relative to the baseline.

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

Shifts in trade volumes and patterns also depend 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 increase in the share of electronics in the total exports – not exceeding 1 percentage point in most countries/regions (only in the case of Indonesia is an increase of 2 percentage points observed) (Figure 9). 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 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 10). 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%.

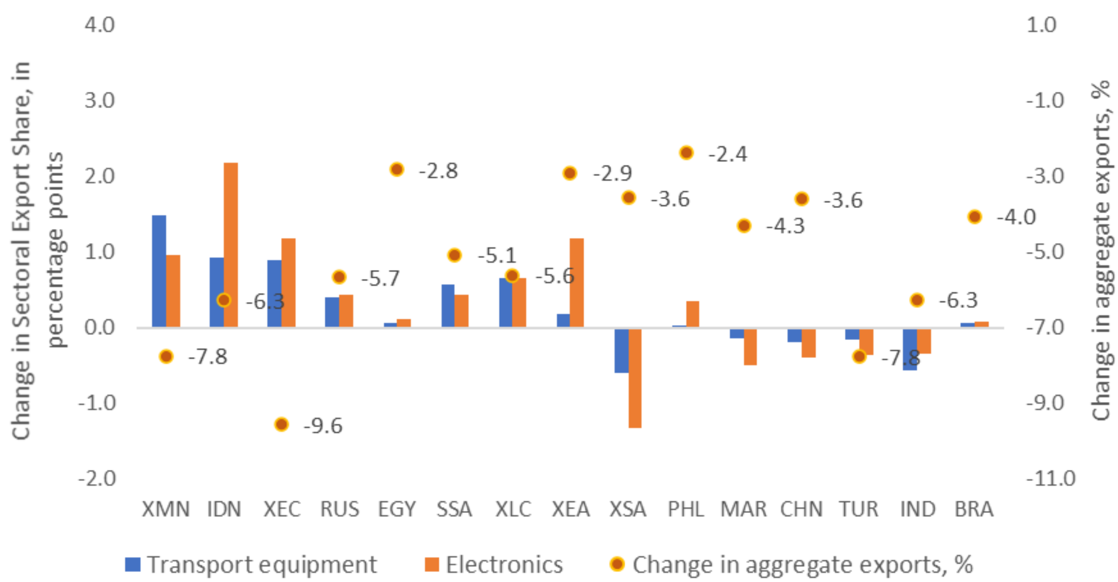

Figure 9. Changes in sectoral export shares and aggregate exports across low- and middle-income countries and regions, under the "2C" scenario relative to baseline in 2050

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. Regional labels are identified in Annex B.

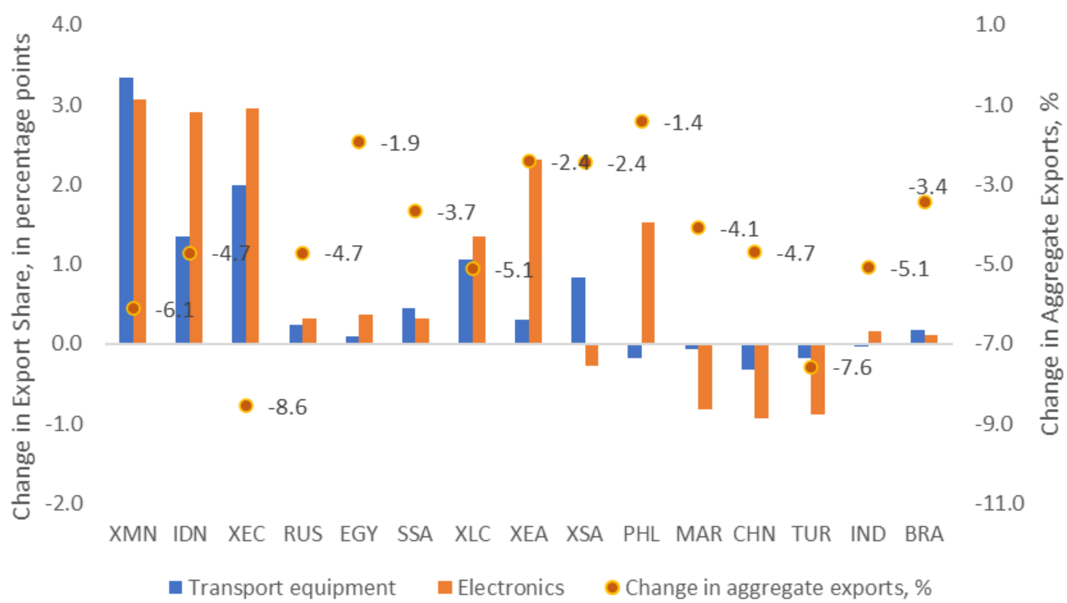

Figure 10. Changes in sectoral export shares and aggregate exports across low- and middle-income countries and regions, under the "2C-FTAX" scenario relative to baseline in 2050

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. Regional labels are identified in Annex B.

Finally, within the context of declining trade-to-GDP ratios relative to baseline, more energy-intensive producers relative to their international competitors tend to experience larger declines. For instance, the

CO_2 emission intensity of India's transportation equipment exports is much higher compared to countries such as the United States, which contributes to the decline of Indian exports of transportation equipment under the "<2c early" scenario compared to the baseline.

The same holds for products within countries. Relatively more energy-intensive products compared to the average emission intensity for all products in a given country tend to decline more. For instance, the average CO_2 emission intensity of all Brazilian exports in 2014 is 1.1 kg/USD. 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. With greater mitigation efforts, Brazil moves away from producing and exporting grains and oil seeds. By the same token, countries that 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 relatively low.

3.4. Impacts on non-fossil fuel exporters

With increased climate mitigation efforts, non-fossil fuel exporters with low emission intensities will become more competitive and may expand or maintain their export volumes even if global sectoral exports decline. The non-metallic minerals sector is the most emission-intensive sector, and its competitiveness is therefore closely linked to the initial emission intensity of production and its evolution over time. All producers reduce their emission intensities in the baseline, but the decline is faster under more ambitious mitigation scenarios (Figure 11). For instance, in the non-metallic minerals sector, the EU27, which already has a strong export position and low emission intensity, increases its exports by 2050 under the "2C" scenario compared with the baseline. The East Asia and Pacific region, also an important exporter of non-metallic minerals but with higher emission intensity than EU27, is expected to see its exports rise by 2050, with similar levels in both scenarios. In contrast, the South Asia region, despite significant reductions in emission intensities, may not gain competitiveness due to having the highest emission intensities among all regions, even under the most ambitious mitigation scenario. While helpful to explain changes in exports across climate scenarios, the emission intensity in a given sector offers only a partial explanation of changes in exports. Changing demand patterns, initial economic structure, emission intensities in other sectors, global value-chain involvement, the ease of resource substitution and reallocation, as well as evolving competitiveness of trading partners will also condition how exports evolve and are reallocated across countries and sectors. However, all pieces of this complex system, even though captured in a dynamic CGE setting, cannot be depicted on a single chart.

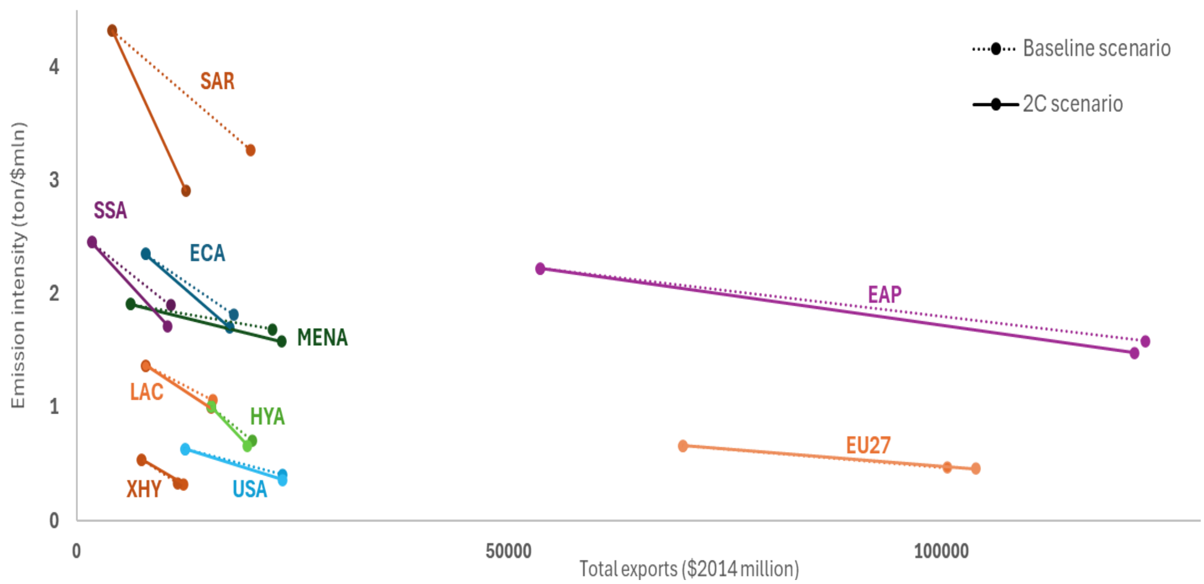

Figure 11: Non-metallic minerals sector exports vs CO2 emission intensities in baseline and "2C" scenarios, by region

Note: Region abbreviations: MENA (Middle East and North Africa), LAC (Latin America and Caribbean), EAP (East Asia and Pacific), SAR (South Asia), ECA (Europe and Central Asia), SSA (Sub-Saharan Africa), EU27 (European Union), USA (United States of America), HYA (High income Asia), XHY (rest of high-income countries).

4. 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 mitigation effort shifts countries' production and comparative advantage from fossil fuel sectors to energy-intensive industries, 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) use a global CGE model GEM-E3 to explore regional and sectoral trade impacts of climate mitigation scenarios focusing on the G20 economies but also reporting the global results. In their 2°C-consistent scenario the authors find that 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 2°C-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 2°C-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 2°C-consistent climate mitigation scenarios. Consistent with the results reported here, Vrontisi et al. (2020) also suggest that the most substantial expansion in economic activity at the sectoral level is observed for the case of clean energy technologies. The 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 results 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.

5. Summary and Conclusions

Using a combination of the ENVISAGE computable general equilibrium, the KINESYS global energy system, and TM5-FASST atmospheric source-receptor models, this study analyzes the economic impacts of different global climate change mitigation scenarios. The paper finds that the energy requires significant policy and investment effort, however, the cost of putting the global economy on a low-carbon transition pathway 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 slowdown 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 as 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.

Inclusion of co-benefits shifts the ledger from economic losses to economic gains. In the analysis, gains from reduced air pollution and related reduction in health burdens were in focus. However, mitigation will also generate direct benefits, due to reduced warming, with further co-benefits including greater preservation of biodiversity.

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. Declines in total exports are registered for all countries, with low- and middle-income countries experiencing a higher magnitude of export reduction (1.6%-6.9% across scenarios).

In terms of trade composition, non-energy-intensive sectors, such as electronics and transportation equipment, gain share 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 relative to baseline with a growing mitigation effort.

In terms of future research, there are several important improvements and extensions that could further advance the analysis 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 of the policy representation, in the current study, we used carbon pricing as a single representative instrument. However, in many countries, governments are implementing a variety of different policies and measures, including subsidies to specific technologies and products, emission standards, and phasing out fossil fuel subsidies. Implementing these country-specific policy instruments would help to provide a more realistic representation of the future impacts of the mitigation policies on global value chains. *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 (Chepeliev et al., 2025). 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. *Fourth,* 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.

Finally, successful mitigation implies a long-run decline in oil demand. This merits attention for at least two reasons. First, oil has traditionally been viewed as a nonrenewable resource whose supply would eventually be exhausted. In this view, accessible oil in the ground is an asset whose value is likely to grow with time. However, a world with declining oil demand opens the possibility that much of the oil currently in the ground will stay there and may eventually become worthless. This creates incentives to extract sooner. Second, incentives to extract sooner notwithstanding, a long-run decline in oil demand must be accompanied by a long-run compression of supply.

Because a sustained decline in global oil demand is unprecedented in the industrial era, how exactly the combination of increasing incentives to extract sooner and a necessary compression in supply will unfold is unknown. This lack of information is particularly relevant in low- and middle-income settings because the share of oil and derived products in total trade tends to be higher in lower-income settings. For example, for sub-Saharan Africa (SSA), oil and derived products represented about 25 percent of total exports and imports in 2022 (WITS 2024). While nearly all countries in SSA tend to import large volumes of fuel, exports of petroleum products tend to be concentrated among a few producers. Future research on the implications of successful mitigation for major net exporters, particularly those with relatively high extraction costs, is important to achieving a relatively smooth energy transition.

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Annex A. Description of the KINESYS 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 time-slices. 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 CO_2.
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, 2024).	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 tCO_2

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 KINESYS model

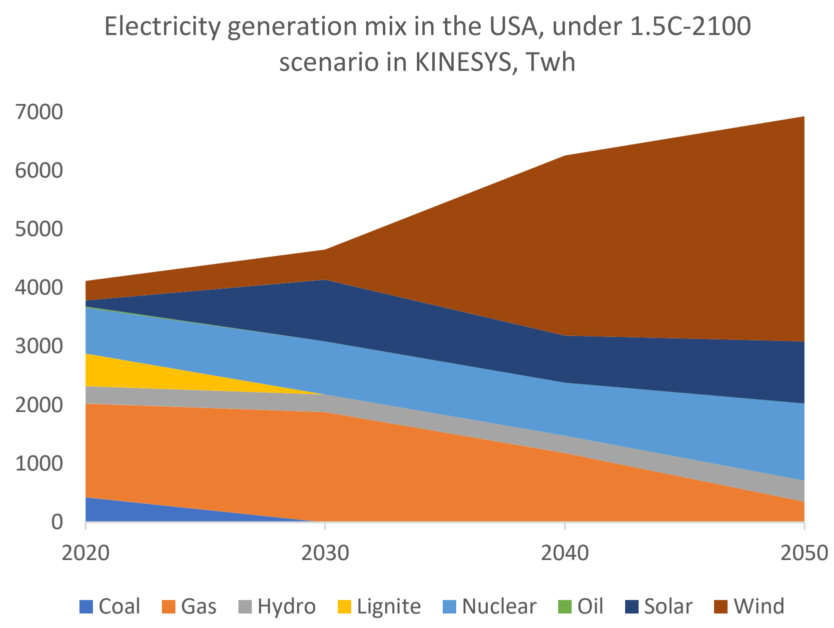

Figure I.1: Electricity generation mix in the USA in the KINESYS model under the 1.5C-2100 scenario, TWh

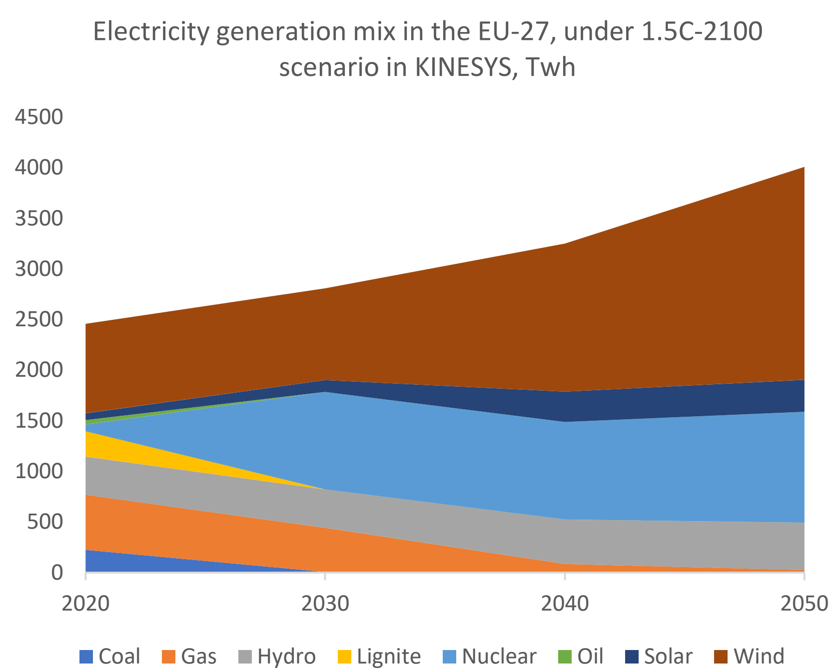

Figure I.2: Electricity generation mix in the EU-27 in the KINESYS model under the 1.5C-2100 scenario, TWh

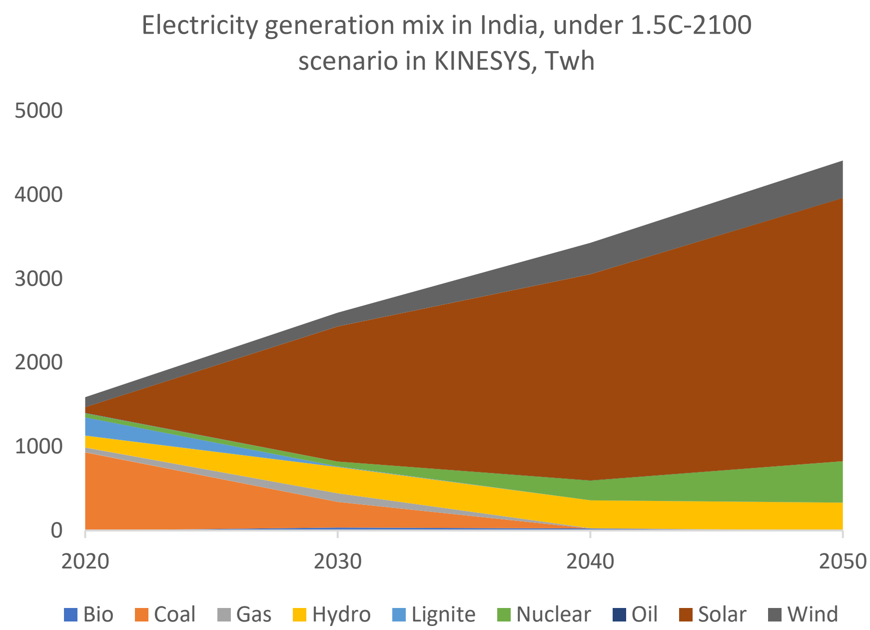

Figure I.3: Electricity generation mix in India in the KINESYS model under the 1.5C-2100 scenario, TWh

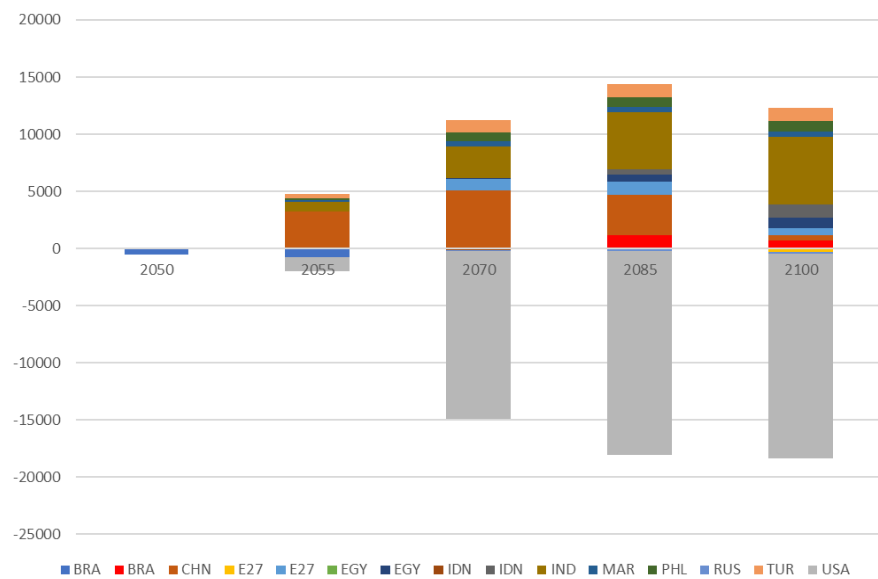

Figure I.4: Change in hydrogen trade in the KINESYS model across countries/regions, under the 1.5C-2100 scenario, in petajoule (PJ). Negative numbers refer to net exports and positive numbers refer to net imports.

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%**