Towards net-zero emissions: impacts on trade and income across and within countries

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Abstract

The impact of a changing climate and the transition to a low carbon world will lead to differing economic outcomes between and within countries. This paper explores global, inter-regional, sectoral and within-region outcomes of shifts in comparative advantage due to policies introduced to mitigate emissions. The latter will lead to significant changes in the energy structures that could lead to dramatic changes in countries' economies and global trade—depending on the nature of the transformation and the policies implemented to achieve greenhouse gas (GHG) emission reductions.

To explore the wide range of outcomes of the future mitigation, this paper applies a multi-model assessment approach, linking together four modelling frameworks. The ENVISAGE global computable general equilibrium model with tracking of GHGs, air pollutants, nutrition indicators and incorporated climate module is used to provide an assessment of socio-economic and environmental impacts across countries. Upstream, ENVISAGE is coupled to a global bottom-up energy system model which provides a set of energy mix profiles used for a better representation of future abatement options. Downstream, ENVISAGE is coupled to the World Bank's Global Income Distribution Dynamic (GIDD) model that estimates the within-country income distribution changes of the various scenarios. Finally, the health-related co-benefits from reductions in air pollution, are identified through use of a global atmospheric source-receptor model TM5-FASST, which estimates changes in premature mortality from various diseases.

This framework is used to explore a set of mitigation scenarios through 2050. The latter include Paris Agreement-consistent mitigation policies and carbon border adjustment measures, as well as (near) net-zero emission scenarios with a limited set of technology variants, such as carbon capture and storage (CCS), high dependency on renewable energy, electrification of ground transportation, hydrogen and combinations thereof.

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1. Introduction

The impact of a changing climate and the transition to a low carbon world will lead to differing economic outcomes between and within countries. This paper explores global, inter-regional, sectoral and within-region outcomes of shifts in comparative advantage due to policies introduced to mitigate emissions. The latter will lead to significant changes in the energy structures that could lead to dramatic changes in countries' economies and global trade—depending on the nature of the transformation and the policies implemented to achieve greenhouse gas (GHG) emission reductions. For example, a sharp move to solar and wind, or other renewables, will drastically reduce the demand for fossil fuels and create a new set of winners and losers in the production and export of energy and energy related goods and services. Taxes on greenhouse gas emissions (or other policies to limit emissions) will change the relative cost of production and prices of goods and alter comparative advantage for sectors across the board inducing changes in trade patterns.

This paper applies the ENVISAGE global computable general equilibrium (CGE) model calibrated to the GTAP-Power Data Base. ENVISAGE has a full accounting of GHGs, an additional 9 local air pollutants, nutrition indicators, a mini-climate module that generates the change in global mean temperature and temperature impact functions (such as on crop yields, labor productivity and sea level rise). With these additions, ENVISAGE is transformed into an Integrated Assessment Model (IAM). Upstream, ENVISAGE is coupled to a global bottom-up energy system model which provides a set of energy mix profiles used to calibrate the parameters of the ENVISAGE model and enabling for a better representation of future abatement options. Downstream, ENVISAGE is coupled to the World Bank's Global Income Distribution Dynamic (GIDD) model that provides the within-country income distribution changes of the various scenarios. Finally, the health-related co-benefits from reductions in air pollution, will be identified through use of a global atmospheric source-receptor model TM5-FASST. This allows for assessment of the impact of mitigation policies on the reduction in premature mortality from various diseases, such as respiratory infections, lung cancer, ischemic heart diseases, strokes, etc.

The climate change mitigation scenarios include:

- A baseline through 2050 calibrated to the World Economic Outlook (WEO) medium term forecast and the long run SSP2 scenario.
- A set of policy scenarios enacted by countries to adapt to the changing world including meeting their Paris commitments and imposing Carbon Border Adjustment Mechanism (CBAM).
- (Near) Net-zero (negative) emission scenarios by 2050 with a limited set of technology variants, for example carbon capture and storage (CCS), high dependency on renewable energy, electrification of ground transportation, hydrogen and combinations thereof. The mitigation scenarios will be stylized using some combination of (optimal) carbon taxes—with and without some form of international cooperation—and directed subsidies. Attention will also be payed to the role that can be played by taxing agricultural emissions—mainly methane and nitrous oxides—that will have impacts on agricultural trade and incomes.

The research applies global economic modelling and country specific analysis to gain a better understanding of those countries and groups that are likely to see new opportunities in a low carbon world and those that are likely to face significant adjustment challenges. Specifically, it assesses the potential impacts of selected climate mitigation scenarios on: GDP, welfare and their distribution across countries; bilateral and sectoral trade; commodity prices; within country distribution of income and an assessment of the global level of poverty. The research concludes with policy recommendations aimed at facilitating the low carbon transition while minimizing the adjustment costs for workers.

2. Data and methods

For the quantitative assessment of the mitigation pathways, we rely on a global recursive dynamic computable general equilibrium (CGE) model—the Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) (van der Mensbrugghe, 2019). An overall accounting framework of the model follows the circular flow of an economy paradigm. Firms purchase input factors (for example labor and capital) to produce goods and services. Households receive the factor income and in turn demand the goods and services produced by firms. Equality of supply and demand determine equilibrium prices for factors, goods and services. The model is solved as a sequence of comparative static equilibria where the factors of production are linked between time periods with accumulation expressions. Production is implemented as a series of nested constant-elasticity-of-substitution (CES) functions the aim of which is to capture the substitutability across all inputs. Production is also identified by vintage – divided into *Old* and *New*—with typically lower substitution possibilities associated with *Old* capital.

Income accrues from payments to factors of production and is allocated to households (after taxes). The government sector accrues all net tax payments and purchases goods and services. The model incorporates multiple utility functions for determining household demand—for this paper, the constant-differences-in-elasticities (CDE) utility function was chosen. Trade is modeled using the so-called Armington specification that posits that demand for goods are differentiated by region of origin. The model allows for domestic/import sourcing at the aggregate level (after aggregating domestic absorption across all agents), or at the agent-level.

The model has two fundamental markets for goods and services. Domestically produced goods sold on the domestic market, and domestically produced goods sold by region of destination. All other goods and services are composite bundles of these goods. Two market equilibrium conditions are needed to clear these two markets.

The model incorporates five types of production factors: 1) labor (of which there can be up to five types); 2) capital; 3) land; 4) a sector specific natural resource (such as fossil fuel energy reserves); and 5) (optionally) water. The labor market is allowed to be segmented (though not required). The model allows for regime switching between full and partial wage flexibility. Capital is allocated across sectors so as to equalize rates of returns. If all sectors are expanding, *Old* capital is assumed to receive the economy-wide rate of return. In contracting sectors, *Old* capital is sold on secondary markets using an upward sloping supply curve.

ENVISAGE incorporates the main greenhouse gases—carbon, methane, nitrous oxides and fluorinated gases, though in the current study we focus only on CO_2 emissions from fossil fuels combustion. A number of carbon control regimes are available in the model. The incidence of the carbon tax allows for partial or full exemption by commodity and end-user. The model allows for emission caps in a flexible manner—where regions/sectors can be segmented into coalitions.

Dynamics involves three elements. Labor supply (by skill level) grows at an exogenously determined rate. The aggregate capital supply evolves according to the standard stock/flow motion equation, i.e. the capital stock at the beginning of each period is equal to the previous period's capital stock, less depreciation, plus the previous period's level of investment. The third element is technological change. The standard version of the model assumes labor augmenting technical change—calibrated to given assumptions about GDP growth and inter-sectoral productivity differences. Detailed documentation 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 2020). 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 18 regions (Appendix A) and 36 sectors (Appendix B).

3. Scenario framework

An overall modelling approach includes, first, development of the baseline scenario that represents future macro, demographic, energy, emissions and other trends under current policy efforts. Then a set of policy scenarios with climate mitigation measures (represented via carbon prices) are developed and compared toward baseline scenario to estimate the policy implementation impacts. Developed scenarios cover 2014-2050 timeframe.

3.1. Baseline scenario

We first develop a ***baseline scenario (BaU)*** that relies on the Gross Domestic Product (GDP) trends from the International Monetary Fund’s (IMF) World Economic Outlook (WEO) (IMF, 2021). IMF’s WEO projections cover 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 demographic trends we rely on projections from the World Bank’s Global Income Distribution Dynamics (GIDD) microsimulation model (Maliszewska et al., 2020).

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, improvements in energy efficiency, increasing share of services and reduction in international transportation costs. Appendixes C and D 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. Appendix D 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.

Under such assumptions, global CO2 emissions moderately increase over time (Figure 1). The growth rate is higher during the 2021-2030 period – around 1.3 percent per year – and slows down to 0.6 percent per year post-2030.

Assumed baseline mitigation efforts substantially vary across countries and regions. Most high income countries manage to achieve substantial reductions in CO_2 emissions in 2050 relative to 2021 – for EU-27 and the Rest of High-income countries the reductions are 20 and 16 percent respectively. Emissions in China peak around 2027-2030 and moderately decrease afterwards. At the same time, in many rapid-growing economies, emissions continue to increase over time and at least double in such countries and regions like India, Indonesia, Egypt, Philippines, Rest of South Asia and Sub Saharan Africa.

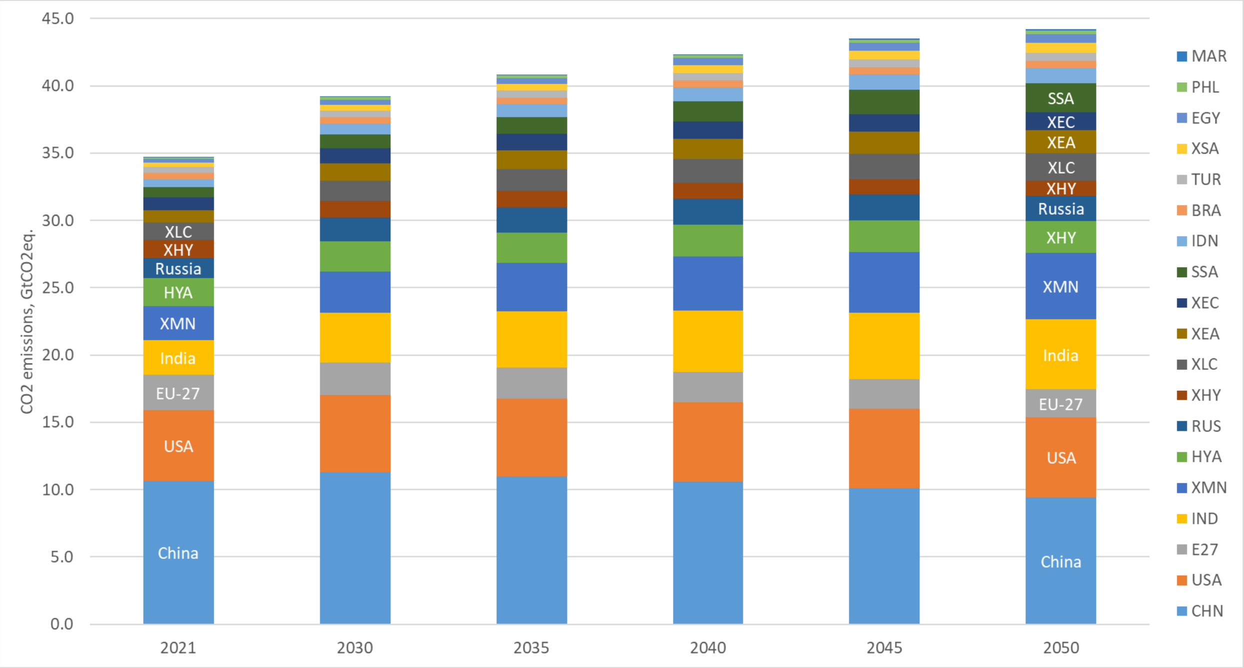

Figure 3.1. Baseline CO2 emissions by regions and years, Gigatonnes (Gt) of CO_2 eq.

As global incomes more than double between 2021 and 2050, demand for energy also increases substantially. At the same time, the energy supply mix in the baseline scenario is still largely dominated by fossil fuels, which are widely used both in transportation sector, as well as for heat and electricity generation (Figure 3.2). Despite dramatic increase in the share of renewables in total primary energy supply – almost six times between 2021 and 2050 – solar, wind and other renewables still represent only 16 percent of total supply at the end of the analyzed period.

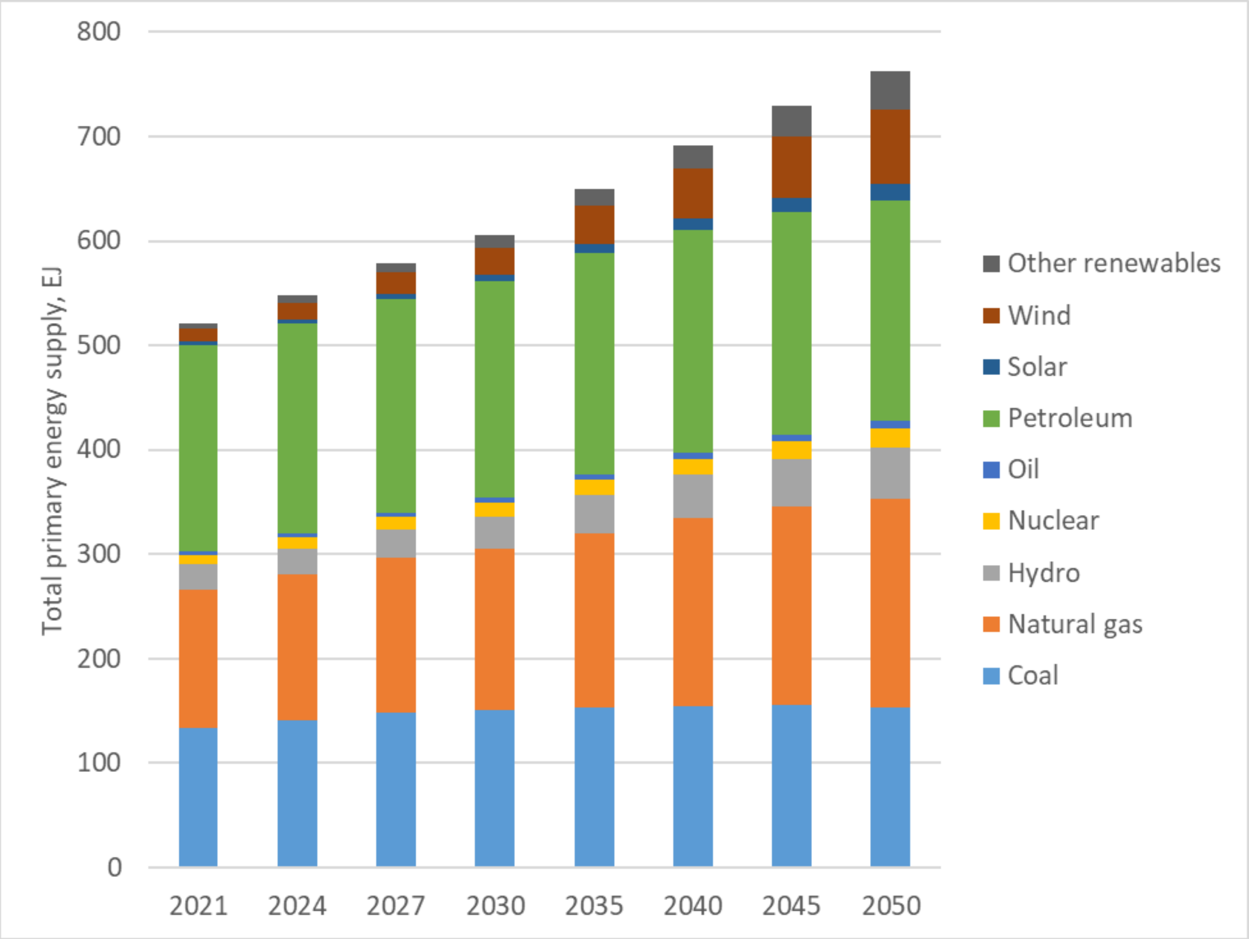

Figure 3.2. Global primary energy supply under the baseline scenario, Exajoules (EJ)

Notes: Primary energy supply is estimated based on the energy balance accounting framework, i.e. no conversion rates for renewable electricity are applied.

With increasing servitization rates (Appendix C), we observe moderate structural shifts at the global level with increasing share of services and decreasing share of light and heavy manufacturing (Figure 3.3). These trends, also being observed at the country and regional levels, represent a structural channel of decarbonization under the baseline scenario. With rising incomes, households' demand shifts more toward services and the share of services in GDP increases. Since services are in general characterized by a lower energy and emission intensity than manufactured goods, this structural transformation contributes to a reduction in GDP energy and emission intensity.

However, as can be seen from an earlier discussion, even when combined with energy efficiency improvements and changes in generation mix, these drivers do not provide enough contribution to outweigh rising population and incomes (demand drivers) and thus fail to achieve absolute reduction in emissions. In what follows, we introduce mitigation policies on top of the baseline scenario that allow to achieve absolute emission reductions. We first explore a scenario with an interpretation of the Nationally Determined Contributions (NDCs) by countries and then move to an assessment of more ambitious mitigation goals.

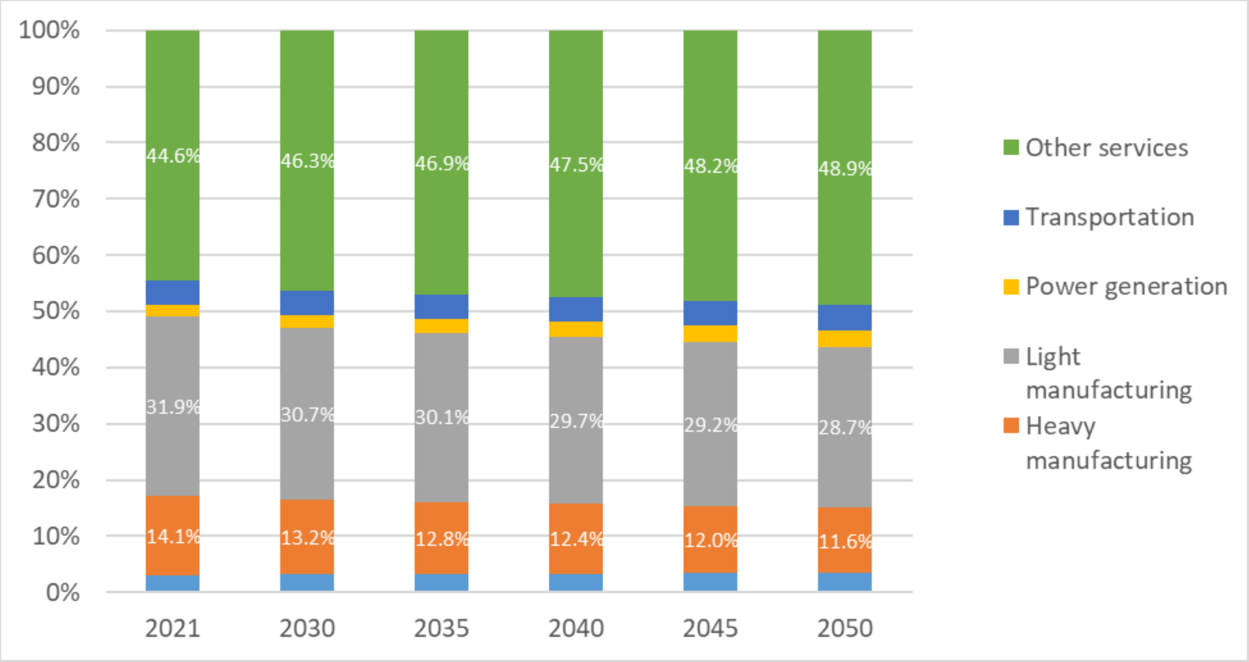

Figure 3.3. Global output structure under the baseline scenario, percent of total output

3.2. Nationally determined contributions

Our first mitigation scenario includes interpretation of the Nationally Determined Contributions (NDCs), as communicated by countries (UNFCCC, 2020).[2] NDC targets are implemented in a form of emission reductions relative to baseline in 2030. Unconditional NDC targets at the country level are adapted from Kitous et al. (2016). These targets are further aggregated using baseline emissions as weights to match the regional aggregation (Appendix A). 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). Figure 3.4 provides an overview of the CO_2 reduction targets relative to baseline emission levels in 2030.

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 price is 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 more broad set of policy instruments within the EU Green Deal package (EC,

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[2] In this assessment, we consider only commitments from the first round of the NDC submissions. Some country-specific adjustments are applied, as further discussed in the document.

[3] https://climateactiontracker.org/

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 to 3%), increase in the sales tax for petroleum products (by 10%), subsidy to renewable generation (5%).

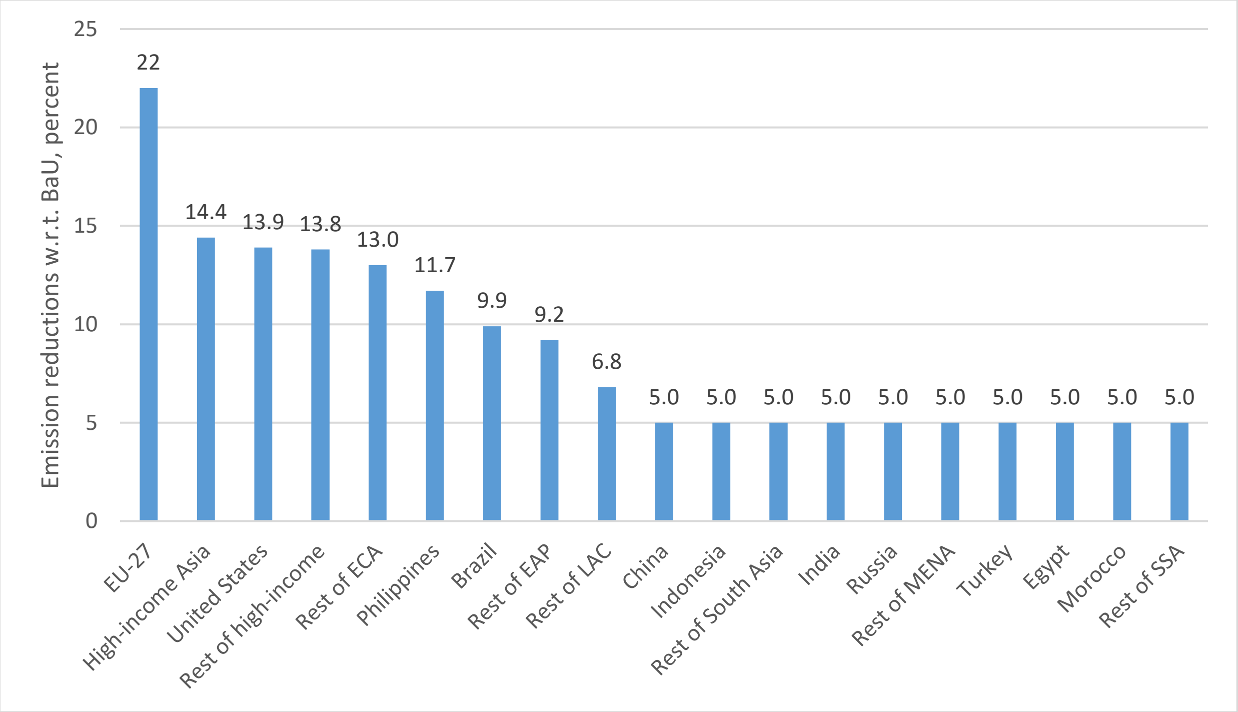

Figure 3.4. CO_2 emission reductions under the NDC scenario in 2030, percent relative to baseline emissions' level

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 EU carbon prices grow at 5 percent per year, while in 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 F 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 few regions have carbon prices above 30 USD per tCO_2 in 2035 (Appendix F). 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 tCO_2 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.

Although in the NDC scenario only a handful of regions implement ambitious mitigation efforts – EU-27 and the Rest of high-income countries together account for less than 5 percent of global emissions in 2030 – even moderate carbon pricing covering all countries of the world is enough to bend the global emissions curve (Figure 3.5). In the NDC scenario global CO_2 emissions peak between 2027 and 2030, and in 2050 decrease by 32 percent relative to the baseline emissions' level.

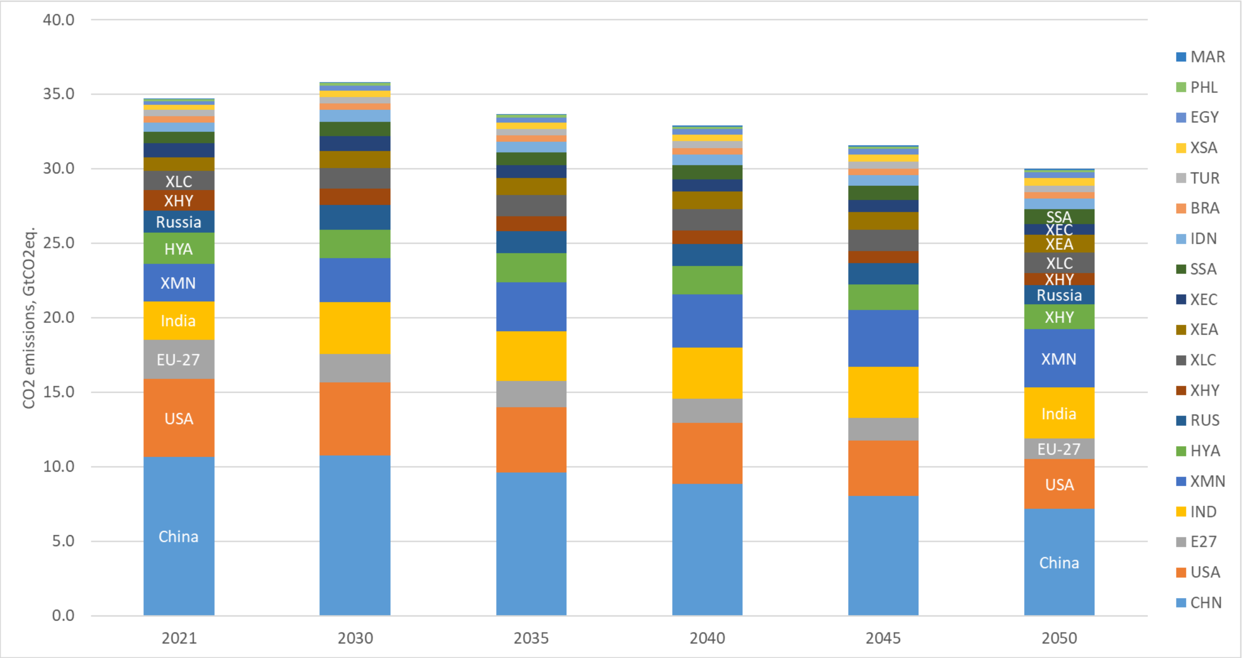

Figure 3.5. CO_2 emissions by regions and years under the NDC scenario, Gigatonnes (Gt) of CO_2 eq.

Emission reductions vary substantially across countries, driven by differences in carbon prices, mitigation costs, baseline emission levels, energy intensities, net trade positions and other factors. Observed reductions range from 20 percent in the Middle East and North Africa region, which is a large energy producer, and exceed 50 percent in Sub-Saharan Africa – a region with high mitigation potential and low abatement costs (partly due to the low price parities). In a number of countries and regions, such mitigation efforts lead to absolute emission reductions over time (in 2050 relative to 2021). In addition to all high-income countries, emission reductions are observed in China, Russia, Europe and Central Asia and Brazil. At the same time, in other developing regions CO_2 emissions continue to grow reflecting strong demand side channel and thus a more ambitious mitigation measures are needed to put a global economy on the low emission development pathway.

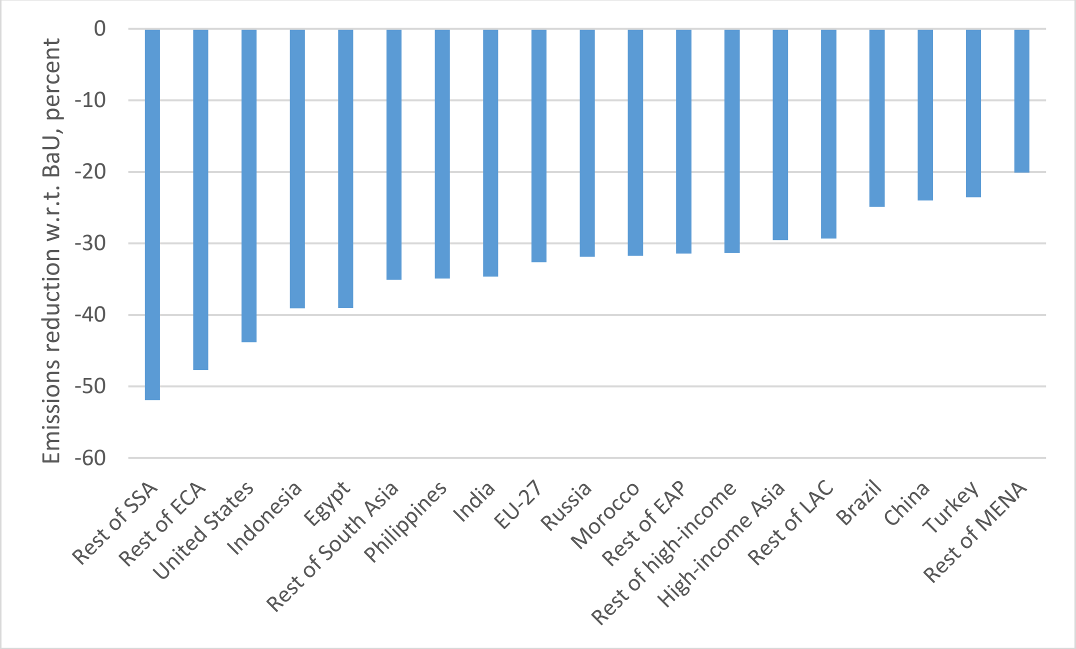

Figure 3.6. Change in CO_2 emissions under by regions NDC scenario in 2050, percent difference relative to baseline level

Moderate carbon prices within the NDC scenario result in substantial transformations in the global energy supply mix (Figure 3.7). *First*, with increasing cost of energy, a reduction in global energy demand is observed – by 2050 aggregate demand falls by around 16 percent relative to the baseline level. *Second*, the share of coal falls substantially over time – from around 26 percent in 2021 to under 10 percent in 2050. *Third*, the share of non-fossil fuel based energy (renewables, hydro and nuclear) increases rapidly – from 10.5 percent in 2021 to over 40 percent in 2050. In terms of added capacities, wind shows the most substantial expansion among all renewable energy sources.

At the same time, petroleum products and natural gas still play a major role in the energy supply mix, contributing almost half of the energy mix in 2050. Substitution of petroleum products in transportation sector still remains limited while gas continues to be widely used in the electricity and heat generation as a lower-carbon substitute for coal.

Energy supply mix substantially varies by countries and regions depending on the level of their mitigation ambition. For instance, in the case of EU-27, coal use is almost entirely eliminated post-2035, while the share of non-fossil fuel-based energy exceeds 58 percent in 2050 (Appendix G). At the same time, the demand for petroleum products in the transportation sector still remains strong, though decreases by 38 percent between 2021 and 2050.

At the global level, we do not find any major structural shifts under the NDC scenario, as the share of services increase by only 0.2 percentage points in 2050 relative to the baseline scenario structure, while the share of manufacturing (heavy and light combined) decreases by 0.4 percentage points (Appendix H).

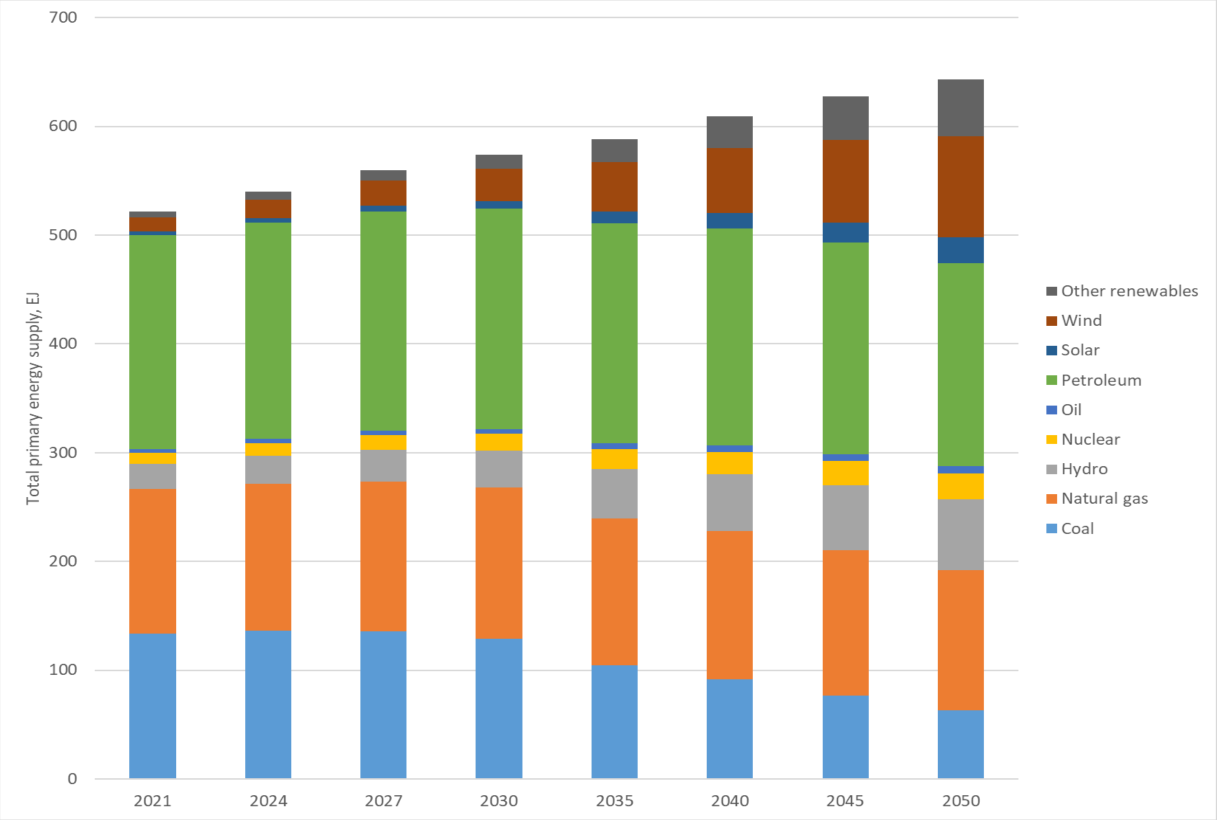

Figure 3.7. Global primary energy supply under the NDC scenario, Exajoules (EJ)
Notes: Primary energy supply is estimated based on the energy balance accounting framework, i.e. no conversion rates for renewable electricity are applied.

Since in the NDC scenario EU-27 is the region with highest carbon prices, in what follows we explore the potential implications of carbon border adjustment measures imposed by EU on all trading partners. After exploring this policy measure we next move to the assessment of a more ambitious mitigation goals, using the NDC scenario as a new reference pathway.

3.3. Carbon border adjustment mechanism implemented by EU

In this section we explore a scenario, where EU acting as a global climate leader imposes a carbon border adjustment mechanism (CBAM) on imports from all sources. CBAM has been proposed as one of the policy measures within the EU Green Deal climate mitigation plan and is aimed at preventing carbon leakage and supporting the EU's increased ambition on climate mitigation (EC, 2021).

To represent the potential impacts of CBAM, we develop a stylized policy scenario, where CBAM is gradually phased in over time with increasing emissions' scope coverage. We impose a CBAM starting from 2024 covering EU ETS sectors and Scope 1 emissions only.[4] Starting from 2030, we increase the emissions' scope coverage by adding Scope 2 and starting from 2035 the CBAM

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[4] https://www.epa.gov/climateleadership/ghg-inventory-guidance-low-emitters

covers all three emission scopes. The CBAM import tax is defined based on the carbon price differential between EU and the country of commodity origin.

In general, we find that such limited CBAM scenario, even in the long-run, has a relatively small impact on EU trading partners (Figure 3.8). In most cases, reductions in real income do not exceed 0.1 percent compared to the NDC scenario level. The two most impacted regions are Russia and MENA, both being large energy exporters that are adversely impacted by the negative terms of trade effect. In these two regions real income decreases by 0.5 and 0.2 percent respective in 2050. Global CO_2 emissions fall by around 0.1 percent following the EU CBAM implementation.

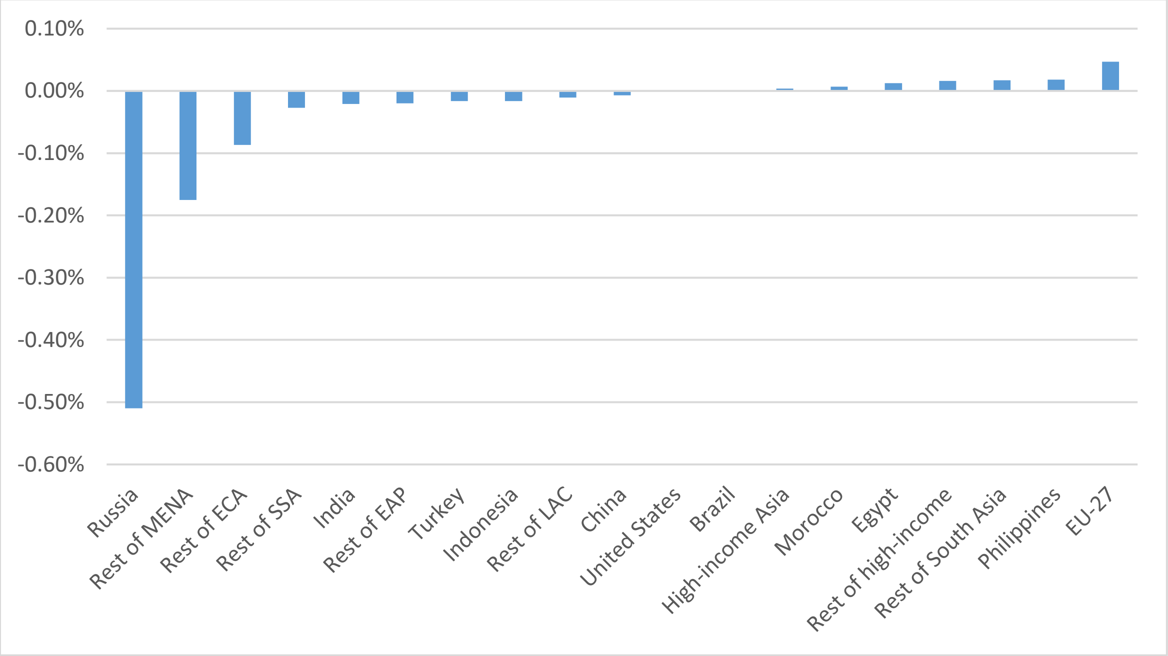

Figure 3.8. Changes in real income under the EU CBAM scenario in 2050, percent difference w.r.t. NDC scenario

A relatively large negative impact on Russian economy is explained by the fact that EU is one of the top destinations for the export of Russia's energy intensive goods, such as chemicals and metals. Following a CBAM implementation, exports of Russian chemicals to EU decrease by over 27 percent in 2040-2050, while exports of metals fall by around 13-16 percent (Figure 3.9). As a result, aggregate exports of chemicals from Russia fall by around 8 percent in the long-run, while exports of metals by around 1-2 percent (Figure 3.9).

While adversely impacting large energy exporters and countries that export energy intensive commodities to EU, the CBAM does not negatively impact and in some cases even benefits other countries and regions, including net energy importers (due to falling global energy prices) and economies that specialize in low carbon intensive goods and services, who receive comparative advantages (Figure 3.8).

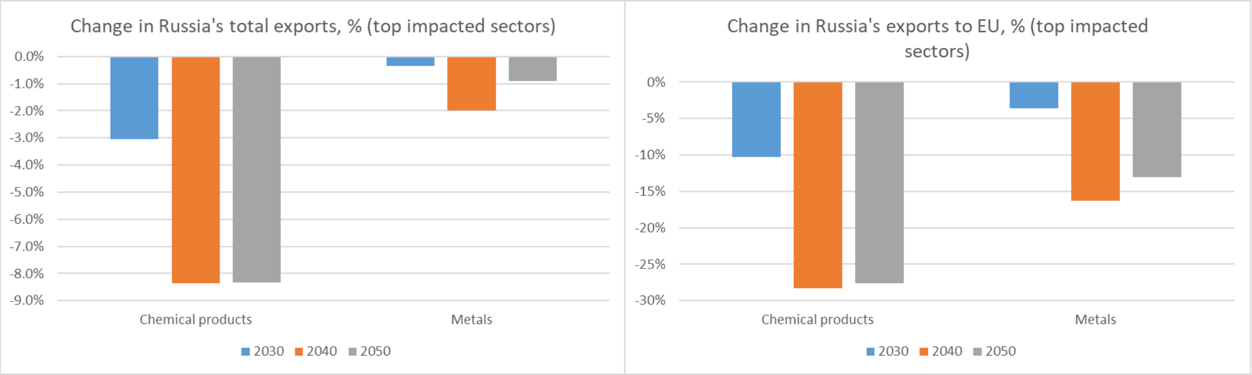

Figure 3.9. Impacts of EU CBAM on Russian exports (selected sectors), percent change relative to NDC scenario

While providing limited support to the domestic EU producers, the CBAM neither does not have any major implications on changes in global emissions (fall by 0.1 percent) nor does it provide any strong motivation for EU trading partners to increase their climate mitigation ambition, leaving a free-ride as a most feasible solution. In this context, a more ambitious mitigation efforts should come directly from other countries. In what follows, we explore such scenarios in detail.

4. Ambitious mitigation scenarios

5. Distributional impacts

6. Conclusion

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Appendix A. Regional aggregation

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	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)
11	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)
12	Rest of South Asia (XSA)	Bangladesh (BGD), Nepal (NPL), Rest of South Asia (XSA), Pakistan (PAK), Sri Lanka (LKA)
13	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)
14	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), Morocco (MAR), Tunisia (TUN), Rest of North Africa (XNF)
15	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)
16	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)
17	High income Asia (HYA)	Hong Kong (HKG), Japan (JPN), Korea (KOR), Taiwan (TWN), Singapore (SGP)
18	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)

Appendix B. Sectoral aggregation

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).

Appendix C. 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.

Appendix D. Assumed shares of renewables in electricity generation under the baseline scenario, percent[5]

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

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[5] Renewables under targeting include, wind, solar and other renewable generation.

Appendix E. Carbon price trajectories assumed under the baseline scenario, 2014 USD per tCO_2

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

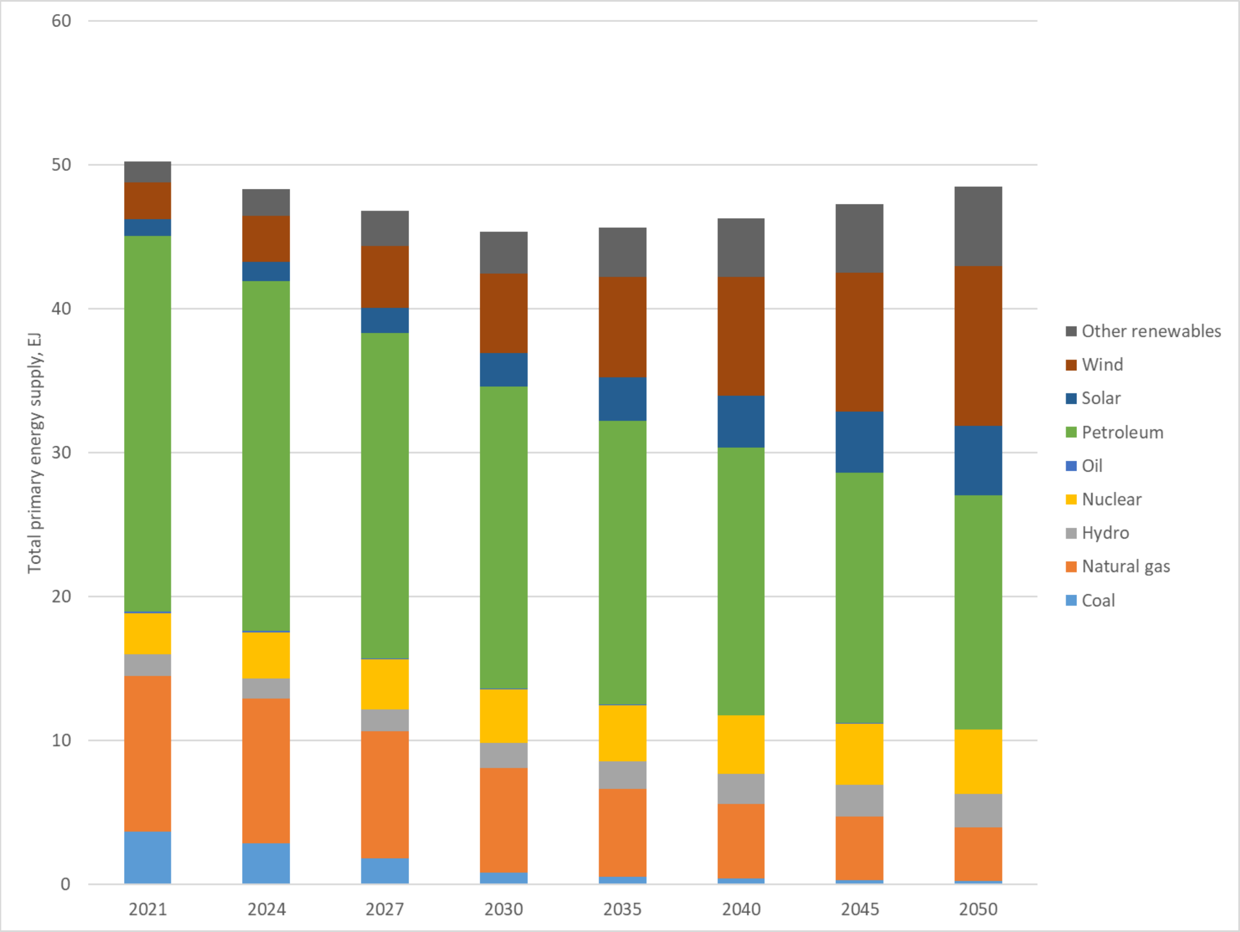
Notes: In the baseline scenario carbon prices are imposed on a selected set of energy-intensive sectors. The latter include chemicals, metals, non-metallic minerals, petroleum products, wood products and electricity generation.

Appendix F. Carbon price trajectories assumed under the NDC scenario, 2014 USD per tCO_2

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.

Appendix G. Primary energy supply under the NDC scenario in EU-27



Notes: Primary energy supply is estimated based on the energy balance accounting framework, i.e. no conversion rates for renewable electricity are applied.

Appendix H. Global output structure under the NDC scenario