GHG emissions, trade balance, and carbon leakage: insights from modeling thirty-one European decarbonization pathways towards 2050

Francesco Clora (fc@ifro.ku.dk), PhD fellow

Department of Food and Resource Economics, University of Copenhagen, Rolighedsvej 23, 1958 Frederiksberg C, Denmark

and

Wusheng Yu (wusheng@ifro.ku.dk), Professor

Department of Food and Resource Economics, University of Copenhagen, Rolighedsvej 23, 1958 Frederiksberg C, Denmark

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Abstract

Recognizing the urgent need for concrete sectoral information in formulating European decarbonization pathways of policy relevance, this study exploits the rich sectoral details from a large bottom-up-built system dynamics model to formulate 31 European decarbonization pathways and creates a tailored-made computable general equilibrium model to evaluate their external effects. Our modeling results suggest that increasing decarbonization ambitions leads to higher reductions of greenhouse gas emissions in Europe (EU27 plus the UK and Switzerland), but with the undesirable outcome of decreasing its external competitiveness through worsened trade balance, if the rest of world does not reciprocate Europe's decarbonization ambition. A comparison of results across pathways with varying ambition levels between demand and supply measures further reveal their differential roles: when keeping demand-side ambitions constant, elevating efforts on the supply side leads to larger emission reductions and bigger decrease in trade balance; however, holding supply-side ambitions unchanged and increasing demand-side efforts improves trade balance while achieving larger emission reductions. Furthermore, ambitious demand measures avoid more losses of net exports when coupled with more ambitious supply mitigation measures. These results point to the need for coordinated demand and supply mitigation actions across sectors, and to the benefits of climate-friendly lifestyle choices in not only reducing emissions but also in avoiding undesirable trade outcomes. Our results also demonstrate positive associations between increasing reductions in GHG emission, worsening external trade balance, and rising carbon leakage rate for the EU. To safeguard the global effectiveness of European decarbonization actions, global cooperation under the Paris Agreement is needed so as to avoid the application of unilateral trade policy such as border carbon adjustments.

1. Introduction

Achieving climate neutrality requires system-wide efforts, combining supply- and demand-side interventions in various sectors of the economy. This is increasingly acknowledged by policymakers (European Commission 2018, 2019) and researchers (IPCC 2014, Creutzig et al. 2016, van den Berg et al. 2019). Climate change mitigation actions include structural changes (e.g. shift away to fossil fuels towards renewable energy sources, modifications to agricultural production systems, etc.), technological development (e.g. more energy-efficient buildings, production processes, etc.), and lifestyle adjustments (e.g. shift towards low-carbon diets, change in mode of transport, etc.). Such actions impose changes to both demand and supply, altering levels and structures of production/consumption across sectors and countries. This, in turn, influences economic dependences across countries such as trade flows and carbon emissions embodied therein. In particular, when a country or a bloc of countries (such as the European Union) conducts unilateral decarbonization, the resulted changes in trade flows may lead to carbon leakage, whereby decreased carbon emissions at home may be partially replaced by rising emissions elsewhere, such as trading partners with weaker or no climate policies in place. Carbon leakage can happen through various channels, such as *competitiveness*, *fossil fuel*, *demand*, and *technological spillovers* (Tan et al. 2018), depending on the supply- and demand-side measures implemented to reduce emissions in a country. While carbon leakage is perceived to be a general concern (European Commission 2019), in practice it often is tied to particular sectors/products, either because of their prominent position in national decarbonization strategies and/or due to their significant trade exposure. Therefore, it is imperative to develop modeling tools and to construct scenarios that can capture these external effects with sectoral details and relevancies.

In the current literature, optimization models (IPCC 2014, Tavoni et al. 2015) are among the most utilized models to simulate economic effects of supply- and demand-side mitigation measures. In these models, mitigation measures are generally implemented through pricing instruments in the context of existing technologies, preferences and policy assumptions. However, it is difficult to implement transformational and non-linear changes in technology and behavior in these models (Rockström et al. 2017), thus limiting their application to explore inter-sectoral synergies and trade-offs in a wide array of decarbonization pathways, including pathways that may generate significant external effects in terms of changing trade flows and carbon leakages. Being able to analyzing these pathways is essential not only from an efficiency perspective (aiming for cost-minimizing pathways), but also from political angles. In fact, social, cultural, infrastructural and regulative reasons can limit the implementation of “first-best” climate policies (Geels 2005, Cagno et al. 2013, Geels et al. 2017).

In contrast, “bottom-up” models that explicitly track sectoral technologies and technical dependencies and material flows across sectors are often more useful in characterizing technical constraints and opportunities in realizing concrete sectoral emission reduction targets. These models are particularly useful in formulating concrete decarbonization pathways – including ambitions pathways of transformational changes as contained in the and in evaluating related technical tradeoffs. One recent example of such models is the European Calculator (EUCalc)[1] model (Pestiaux et al. 2019), which belongs to the so-called calculator model family (Allen and Chatterton 2013, Pidgeon et al. 2014, Spataru et al. 2015, Butler et al. 2015, Demski et al. 2015, Codina Gironès et al. 2015, Elizondo et al. 2017, Strapasson et al. 2017, Demski, Spence, and Pidgeon 2017, Chatterton 2017, Moinuddin and Kuriyama 2019, Strapasson, Woods, Meessen, et al. 2020, Strapasson, Woods, Pérez-Cirera, et al. 2020, Berger et al. 2020, Füllemann et al. 2020). The EUCalc model has been used for studying the interactions of changes to lifestyle, production structures and technologies as mandated by the decarbonization ambition of the EU, United Kingdom and Switzerland (EU27+2 or Europe

[1] https://www.european-calculator.eu/

for short). Unlike top-down (TD) models often based on carbon pricing instruments, EUCalc is built on bottom-up (BU) modules that account for changes specified at variable ambition levels across 15 energy-relevant demand-side decisions and more than 50 sectoral technologies (see Figure 1), thereby allowing for the exploration of numerous alternative European decarbonization pathways, including pathways that are not analyzed by other models. This model provides a unique opportunity to analyze the external effects of the EU's decarbonization efforts with detailed and explicit sectoral and technological underpinnings. However, as in typically bottom-up models, the lack of market connections and price mechanisms make it difficult to obtain results on economic impacts.

In this study, we build a modeling approach to evaluate scenarios developed from the EUCalc model with sectoral, technological, and behavioral details in a top-down economic modelling framework. This is achieved by developing a detailed interface that "translates" bottom-up decarbonization pathways into scenarios implementable in the economic model on the one hand, and by extending a well-known economic model of the CGE variety with more robust and flexible behaviors to accommodate large changes in exogenously defined decarbonization scenarios on the other hand. For the latter point, we make use of the energy- and climate-focused version of the GTAP model and apply several key modifications, resulting in a modeling system nicknamed GTAP-EUCalc (Clora and Yu 2020). This modelling approach represents a valuable attempt to bridge the gap between pure economic optimization models and bottom-up calculator models. This is the methodological contribution of the paper. As an application of the modeling approach, we quantify and compare the external impacts (in terms of trade flows and carbon leakage) of 31 alternative EU decarbonization scenarios consisting of sector-specific demand- and supply-side mitigation measures at various ambition levels. A careful analysis of simulation results from these scenarios reveals the potential options across sectors and ambition levels in achieving a decarbonized EU economy, and the tradeoffs between maintaining economic competitiveness and ensuring the global effectiveness of Europe's decarbonization strategy. This is the second major contribution of the study.

This article is structured as follows. Section 2 describes the methods, focusing on the integration of the EUCalc core modules with the GTAP-EUCalc model. Section 3 defines the scenarios. Key results are presented in Section 4. The last section concludes.

2. Model, baseline and scenarios

2.1 The EUCalc model

The EUCalc is a model of energy, land, materials, product and food systems at EU27+2 aggregate and member states levels for representing GHG emissions dynamics until 2050 (Pestiaux et al. 2019). It builds on the experience of the Global Calculator (Strapasson, Woods, Pérez-Cirera, et al. 2020) and other existing calculator models (Spataru et al. 2015, Berger et al. 2020), which have been used to assess climate global and regional mitigation potentials, and for evaluating users' preferences for energy futures (Demski, Spence, and Pidgeon 2017, Pidgeon et al. 2014, Demski et al. 2015). At its core, the EUCalc has the so-called *ambition levers*, which allow users to exogenously control trajectories towards 2050 for more than 50 supply- and demand-side dimensions that can affect GHG emissions. Each lever can be set at four different levels of mitigation ambitions: the continuation of observed trends (ambition level 1), intermediate ambitions above but falling short of potential (level 2), very high ambition but realistic vis-à-vis current technology evolutions and the best practices observed in some geographical areas (level 3), and ambitions requiring transformational changes (level 4). Levers and the associated ambition levels are identified in consultations with sectoral experts and stakeholders during a series of co-creation workshops (Rankovic and Patrick-Kelly 2019), following literature reviews on mitigation options in each of the EUCalc sectors. Alternative decarbonization pathways can be constructed and evaluated by choosing a combination of ambition levels for the full set of levers available to the users.

The EUCalc is composed of interdependent modules, representing core activities and energy-relevant sectors of the economy (Figure 1). In addition to the sectoral modules designed following a BU modelling approach, the EUCalc contains several modules outside of the modeling core for assessing socioeconomic impacts, e.g. transboundary (Clora and Yu 2020) and employment (Thurm and Vielle 2019) effects, of user-defined decarbonization pathways. The transboundary module, in particular, is developed to evaluate the external effects of European decarbonization pathways.

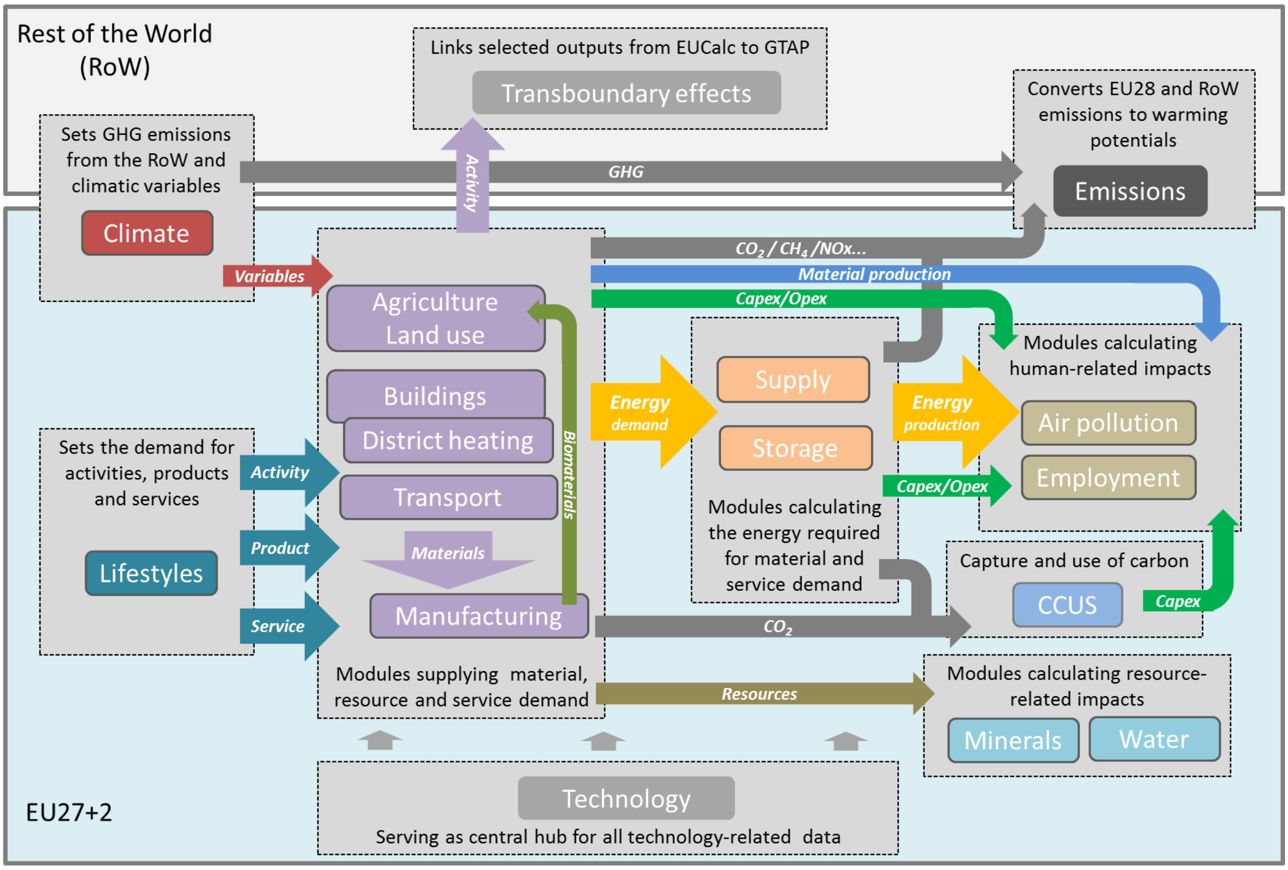

Figure 1 - Modular structure of the European Calculator model (Costa et al. 2020)

2.2 The GTAP-EUCalc model and 2050 baseline

While allowing for constructing and exploring a wide range of EU27+2 decarbonization pathways with complex technical linkages within and across key sectors, the core modules of the EUCalc model does not have built-in market and price mechanisms to evaluate the external effects of EU27+2's decarbonization efforts, such as changing external trade patterns and carbon emissions embodied in trade flows. Economic models such as computable general equilibrium (CGE) models are well suited for this purpose. CGE models are a typical tool for empirical analysis of distributional and welfare impacts of various policies (Winters and Hertel 2005, Anderson and Martin 2005, Bandara and Yu 2003), and are also used in evaluating climate change mitigation policies (Babatunde, Begum, and Said 2017, Riahi et al. 2017, Bauer et al. 2020, Babiker 2005, Böhringer, Balistreri, and Rutherford 2012, Vandyck et al. 2016, Roelfsema et al. 2020). When used in conjunctions with models with more BU details, CGE models can provide insights into the economic consequences of concrete decarbonization scenarios. This points to the need of linking the two different types of models, as has been done extensively in analyzing global climate policy.

According to Labriet et al. (2015), there are different ways in linking bottom-up and top-down models in the climate policy literature. The methodologies assessed include (1) linking models via the exchange of data while running the models independently, (2) integrating technology details in TD models (e.g. calibrating production functions in TD models with the responses of BU models), (3) augmenting the BU model with equations coming from the TD model, and (4) fully integrating TD and BU models within the same optimization framework. In our study, given the different architectures of the EUCalc model and a CGE model, we link the two models in a fashion similar to the first methodology, redesigning a well-known CGE model to add flexibilities so that it can accommodate large changes implied by more ambitious pathways obtained from the EUCalc BU modules. A modeling interface is also designed so as to consistently and systematically harness the rich engineering details from the EUCalc pathways and parsimoniously represent them as modeling inputs into the CGE model. Based on the GTAP-E model (Burniaux and Truong 2002, McDougall and Golub 2007), an energy- and climate-oriented version of the widely used standard GTAP model (Hertel et al. 1997), we develop the GTAP-EUCalc model (Clora and Yu 2020). The model incorporates a modified private demand system with embedded within-budget share shifters (Dixon and Rimmer 2002) to capture preference-driven modifications to the private demand for energy and non-energy commodities. As proposed by Dixon and Rimmer (2002) and applied by e.g. WTO (2018), the model also includes a twist-parameter in each nest of the CES production structure allowing for changes in cost shares; this feature is implemented to facilitate the modeling of technological and structural changes in many of the EUCalc sectors, according to their lever settings. The GTAP-EUCalc model also features an isoelastic aggregate supply of land at the regional level, to capture changes in total land use due to alternative agricultural systems and food demand. Finally, we add to the model a number of equations to integrate the GTAP v9 non-CO2 database (Irfanoglu and van der Mensbrugghe 2015) and capture overall GHG trends[2].

For this analysis, we use the GTAP-E v9 database (Aguiar, Narayanan, and McDougall 2016) and the GTAP non-CO2 dataset (Irfanoglu and van der Mensbrugghe 2015), with 2011 as a reference year. The two databases – originally disaggregated by 57 sectors and 141 countries/regions – are aggregated to 18 sectors, 18 regions/countries in the EU27+2, and 15 regions/countries in the Rest of the World[3]. Simulations of EU27+2 decarbonization scenarios are conducted against a business-as-usual (BAU) global baseline in 2050, projected in accordance with the latest available literature (Foure et al. 2020, Chateau et al. 2020). To build the baseline, the GTAP databases are updated to 2050 in 5-year intervals, using recent projections on GDP (European Commission et al. 2016, Dellink et al. 2017), population (European Commission (DG ECFIN) and Economic Policy Committee (AWG) 2015, Kc and Lutz 2017), and labor force (Fouré and Fontagné 2016, European Commission (DG ECFIN) and Economic Policy Committee (AWG) 2015). These projections are consistent with the EU Reference Scenario 2016 (European Commission et al. 2016) and with the “middle of the road” Shared Socioeconomic Pathway (SSP2) (Fricko et al. 2017). In addition, we implement in the baseline differential sectoral productivity estimates of Bekkers et al. (2019) and exogenously projected changes in fossil fuel prices (IEA 2012, 2017). Finally, the EU Reference Scenario electricity generation mix defined with the EUCalc model is reproduced.[4] Relative to the 2050 baseline, the lowest ambition level specified in the EUCalc model (i.e. level 1) actually lags behind, due to the fact that the EU Reference Scenario

[2] Section 1 of the Supplementary Materials contains an expanded description on how these features are implemented.
[3] Aggregation details can be found in Section 2 of the Supplementary Materials.
[4] Further details regarding the baseline can be found in Section 3 of the Supplementary Materials.

represents more ambitious climate mitigation as compared to current trend. In contrast, ambition levels 2-4 in the EUCalc exceed the baseline.

2.3 Interfacing EUCalc decarbonization pathways and GTAP-EUCalc scenarios

Decarbonization pathways in the EUCalc model are driven by a set of assumptions (levers) in six core modules, namely, *lifestyle choices*, *buildings*, *transport*, *manufacturing*, *agriculture and land use*, and the *energy system*. In each module, a set of decarbonization ambitions is defined on one or more key behavior or technological variables, which are known as "levers" in the model. Based on the differences between the ambition level for a lever (i.e. lever settings) and its initial/baseline level, a percentage shock can be derived and used as inputs of the scenarios to be implemented in the GTAP-EUCalc model. To bridge the differences in sectoral granularities, appropriate aggregation schemes are developed to aggregate inputs from EUCalc pathways for use in the GTAP-EUCalc model. Table 1 presents the main inputs obtained from individual EUCalc modules and the corresponding variables in the GTAP-EUCalc model, grouped in the aforementioned six modules.

As the EUCalc model envisions ambitions in key behavioral and technical changes in key sectors but does not consider the economic "instruments" for realizing such changes, some of these changes have to be imposed either directly or indirectly in the economic model. For instance, lifestyle changes (e.g. dwelling, food consumption, transportation and travel behavior, and other household consumption of energy intensive products – see Table 1) are typically driven by economic incentives such as changes in income, prices, and/or government regulations. In the absence of such incentives, we model lifestyle changes as autonomous changes in consumer preferences, implemented by changing preference shifters in the demand system in the model. Similarly, changes in intermediate demand (e.g. the use for transportation services by other sectors, or energy system transition towards more renewables and less fossil fuel) are implemented by altering cost structures in the relevant sectors. A third type of changes that are built on the expectations that efficiencies in production or in energy consumptions improves are modeled as efficiency improvements either related to outputs (e.g. increasing yields in agriculture) or certain inputs in the production (e.g. improved energy efficiency in residential buildings, transportation, and manufacturing).[5]

The simultaneous changes to the demand and supply functions in the EU27+2 countries/regions, arising from implementing the EUCalc pathways, may create gaps between domestic demand and supply at the initial domestic market price levels. To restore market equilibrium, domestic prices market must adjust; however, changing domestic market prices will trigger further adjustments in the EU27+2's internal and external trade flows, as the EU27+2 not only has an integrated common internal market linking member states but also heavily conducts international trade with external trading partners. As such, there will also be ripple effects across the rest of the world in the forms of changing trade flows into and from the EU. These effects are captured in the GTAP-EUCalc model via the Armington specification (Armington 1969).

[5] Details on how inputs from each module are transformed into exogenous shocks to the 2050 baseline are summarized in Section 4 of the Supplementary Materials.

Table 1 – Inputs from individual core modules and 'translation' into economically relevant exogenous shocks against the 2050 baseline in GTAP-EUCalc

Inputs from module	Module documentation	Inputs from EUCalc	Processed inputs to GTAP-EUCalc (% from baseline)	Additional references
Lifestyle	Costa, Waibel, et al. (2020)	Floor intensity per capita Passenger travel per capita Food demand [30 food groups] Paper and plastic packaging Sanitary and graphics paper Aluminium and glass packaging Number of appliances [8 groups]	Household demand for dwellings Household demand and intermediate demand by the service sector for 3 food commodities Household demand for 2 manufacturing products	Costa, Moreau, et al. (2020)
Transport	Taylor et al. (2019)	Passenger-kilometres [25 technologies] Tonne-kilometres [34 technologies] Number of vehicles per technology [25 + 34 technologies] Energy demand per technology [25 + 34 technologies]	Intermediate demand for 3 transport services by core sectors Household demand for 3 transport services Energy efficiency for 3 transport sectors Capital efficiency for 3 transport sectors Intermediate demand for electricity and oil products by three transport sectors Household demand for 5 energy commodities (with 'buildings' module)	
Buildings	Kockat and Wallerand (2019)	Floor area [6 building types] Energy consumption [6 energy carriers, 6 building types] Energy consumption [9 district heating carriers]	Household demand for 5 energy commodities (with 'transport' module) Energy efficiency of residential and non-residential buildings	
Manufacturing	Warmuth et al. (2020)	Industry output [8 industries] Energy demand [8 industries, 9 energy carriers]	Energy efficiency for 2 manufacturing sectors intermediate demand for 2 energy bundles by 2 manufacturing sectors	
Agriculture and Land Use	Baudry, Mwabonje, and Woods (2019)	Crop production [11 crop types] Animal food production [9 categories] Livestock population [7 animal types] Agricultural land Fertilizer consumption [4 fertilizer types]	Crop yields Livestock yields Intermediate demand for fertilizer by the crop sector	Strapasson, Woods, Meessen, et al. (2020)
Power	Gyalai-Korpos, Hegyfalvi, and Zsiborács (2019)	Electricity production [12 generation technologies]	Cost shares of capital, coal, oil, gas, oil products and services in the electricity sector, based on 8 electricity-generating sectors cost structures in the GTAP Power v9 database (Peters 2016)	(Gyalai-Korpos et al. 2020)

3. Scenarios

The GTAP-EUCalc model is a CGE model with stringent optimization conditions and a complex sectoral, inter-sectoral and inter-national linkages and feedbacks. Solving CGE models generally is time-consuming and also requires a precise calibration of the changes implemented in each scenario. Therefore, instead of generating trade-related results for the numerous EUCalc pathways, in this study we simulate a subset of decarbonization scenarios that are meaningful and relevant at the sectoral dimension (Table 2).[6] These scenarios are selected from a co-design process with sectoral experts and other stakeholders and can be classified into three groups (Rankovic and Patrick-Kelly 2019).

[6] While ambition levels can very well vary across EU member states in reality, all pathways considered in this study assume uniform ambitions across the EU member states. This allows us to focus on the effects arising from the different combinations of sectoral ambitions. Also worth noting is that several demographic levers (e.g. population) are left unchanged from the baseline level in all scenarios. Mitigation efforts in the rest of the world are also assumed to be unchanged from the baseline. A detailed description of the lever settings can be found in Clora and Yu (2020).

In the first group, labeled P1 to P4 in Table 2 (with level 1 representing the least ambition and level 4 representing the highest possible ambition), all levers are set at uniform ambition levels for all sectors and countries in the EU27+2, representing a common decarbonization strategy across sectors and countries. These pathways can be considered as benchmark pathways because of the uniformity in ambition levels.

Table 2 - Definition of EU27+2 decarbonization pathways[7]

	Demand-side groups of levers				Supply-side groups of levers				
Pathway	**Travel**	**Homes**	**Diet**	**Consumption**	**Transport**	**Buildings**	**Manufacture**	**Power**	**Land & Food**
Set 1 (uniform efforts)									
p1	1	1	1	1	1	1	1	1	1
p2	2	2	2	2	2	2	2	2	2
p3	3	3	3	3	3	3	3	3	3
p4	4	4	4	4	4	4	4	4	4
Set 2 (demand vs supply efforts)									
p5	1	1	1	1	2	2	2	2	2
p6	1	1	1	1	3	3	3	3	3
p7	1	1	1	1	4	4	4	4	4
p8	2	2	2	2	1	1	1	1	1
p9	2	2	2	2	3	3	3	3	3
p10	2	2	2	2	4	4	4	4	4
p11	3	3	3	3	1	1	1	1	1
p12	3	3	3	3	2	2	2	2	2
p13	3	3	3	3	4	4	4	4	4
p14	4	4	4	4	1	1	1	1	1
p15	4	4	4	4	2	2	2	2	2
p16	4	4	4	4	3	3	3	3	3
Set 3 (D&S sectoral combo)									
p17	3	2	2	2	3	2	2	2	2
p18	2	3	2	2	2	3	2	2	2
p19	2	2	3	2	2	2	2	2	3
p20	2	2	2	3	2	2	3	2	2
p21	2	2	2	2	2	2	2	3	2
p22	4	2	2	2	4	2	2	2	2
p23	2	4	2	2	2	4	2	2	2
p24	2	2	4	2	2	2	2	2	4
p25	2	2	2	4	2	2	4	2	2
p26	2	2	2	2	2	2	2	4	2
p27	4	3	3	3	4	3	3	3	3
p28	3	4	3	3	3	4	3	3	3
p29	3	3	4	3	3	3	3	3	4
p30	3	3	3	4	3	3	4	3	3
p31	3	3	3	3	3	3	3	4	3

The second set of pathways – consisting of 12 pathways (from P5 to P16) – aims at exploring differential effects of mismatching decarbonization ambitions on the demand- and supply-side levers by placing these two sets of levers at different positions. The demand-side levers concern consumer behavioral choices on travel, home (residence), diet, and (household) consumption, whereas the supply-side levers include those on transport, buildings, manufacturing, power, and land and food. For instance, when consumers choose very high ambitions on diet and largely move away from meat consumption but the land & food sector stays at the lowest ambition level by continuing to produce animal food products without significant changes in

[7] Lever setting 1 (in red) implies a continuation of past trends; lever setting 4 (in green) implies transformative changes on the supply- and demand-side to abate GHG emissions.

yields and without major reductions in energy and chemicals use, it is then expected that agricultural & food sector would not contribute much to EU27+2's decarbonization efforts, as part of the excess domestic food production would lead to increased net exports. Conversely, when consumers have limited ambition in reducing their consumption behaviors (e.g. home appliances, paper and plastic packaging, etc.) but the manufacturing sectors undergo ambitious decarbonization efforts through modifications to their production function (e.g. substituting materials with more sustainable alternatives, changing the fuel mix, etc.), it can be expected emissions in the EU27+2 to decrease, but manufacturing production in the rest of the world to increase.

In the third set of pathways, ranging from P17 to P31, we allow in each pathway the ambition levels in both the demand and supply levers in one particular sector to match but differ from the uniform ambition level set for all other sectors. More specifically, in each pathway, we allow one of the following pairs of levers to be set a different level from all the other levers: travel and transport, home and buildings, (household) consumption and manufacturing, diet and land & food. These pathways can reveal the sensitivities of the overall mitigation effects to the particular decarbonization ambition applied in particular sectors.

4. Results

Focusing on the external effects of the EU27+2 decarbonization pathways studied in this paper, we first use two representative pathways – the most and least ambitious pathways with uniform efforts across sectors (P4 and P1, respectively) – to illustrate and explain the modeling mechanisms that drive the main results on trade flows, changes in trade balance, and carbo leakages. We then proceed to summarize the aggregate impacts on GHG reduction, changes in trade balance, and carbon leakage from all the 31 scenarios simulated.

4.1 Key results from two representative scenarios

Table 3 presents the simulated changes in the EU27+2's external exports, imports and trade balance with ROW, as compared to the 2050 baseline, and the associated carbon leakage rate. In scenario P1 where the EU27+2 is actually assumed to reduce its climate mitigation ambitions relative to the 2050 baseline, the EU27+2's net trade balance with ROW is expected to improve by US$352 billion, led by an increase in exports and a slight decrease in imports. On the contrary, in scenario P4 where the EU27+2 implements the most ambitious climate mitigation strategy, simulation results suggest that the exports to ROW would decrease and imports would increase at the same time, leading to a deteriorated trade balance by US$863 billion. Underlying the decreased external exports and rising external imports are decreasing production activities in the EU27+2 and rising production activities in ROW, suggesting reallocation of GHG emissions associated with production activities from the EU to ROW. Indeed, the carbon leakage rate obtained from P4 is 61.5%, indicating that, for each tonne of CO_2e reduced in the EU, the ROW would increase its GHG emissions by approximately 0.615 tCO_2e. To understand these aggregated results, further details on changing bilateral trade patterns across trading partners are provided in Figure 2. Likewise, further details on changing trade patterns across sectors are provided in Figure 3.

Table 3 - Change in EU27+2's external trade and trade balance (bln USD), and carbon leakage rate, relative to baseline.

	Export	Import	Trade Balance	Carbon leakage rate
P1 - base	325	-26	352	n/a[8]
P4 - base	-520	343	-863	61.5%

[8] The carbon leakage rate in this case is not a meaningful measure, as the EU27+2 would be increasing its emissions with respect to the baseline scenario.

In scenario P4, with very ambitious climate efforts in the EU27+2 (but no change in ROW climate efforts), the EU27+2's balance of trade with Russia, the rest of Europe and other Former Soviet Union (FSU) countries would improve. Additionally, we observe a decrease in imports from Middle East and North Africa (MENA). These changes are mainly due to reduced EU27+2 demand for fossil fuels (e.g. oil and gas, of which EU27+2 has historically been a net importer (Eurostat 2016)), as a result of the EU27+2's across-the-board ambitious decarbonization efforts. We also note that there is a simultaneous decrease in exports and increase in imports with other countries and regions (especially China and the US), mainly driven by the deteriorating trade balance in sectors such as manufacturing and services. In contrast, lower ambitions as in P1 lead to an opposite situation where the EU27+2's imports from countries and regions exporting fossil fuels (i.e. Russia, rest of Europe, other Former Soviet Union countries, Middle East and North Africa) increase, and its trade balance with other major economies improves. While not shown, results from scenarios with the intermediate ambitions (i.e. P2 and P3) lie in between of the results obtained from P1 and P4, as expected. While these results tend to suggest worsening trade balance for the EU27+2 when it conducts ambitious decarbonization, it is important to note that such results are based on the assumption that the rest of world would not pursue similar mitigation action.

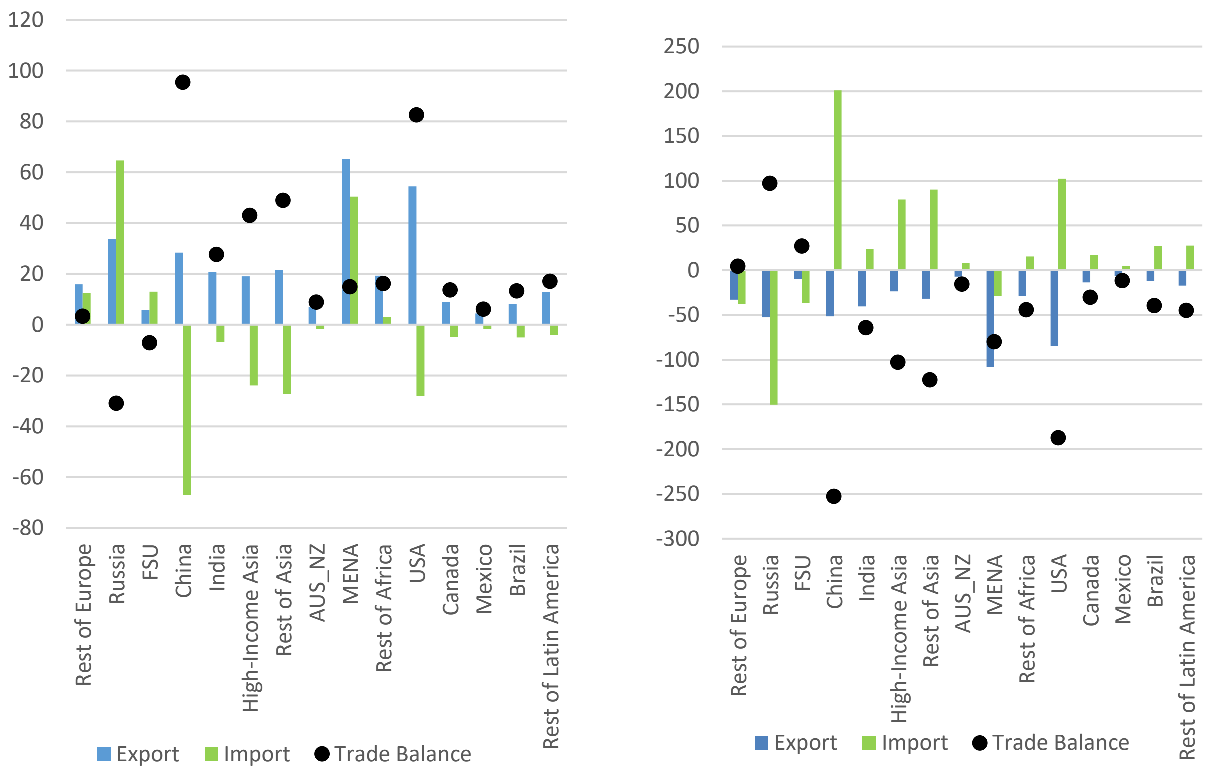

Figure 2 Change in aggregate trade of EU27+2 vs ROW economies in P1 (left) and P4 (right), relative to baseline (bln USD).

Simulated changes in the EU27+2's external trade patterns by sectors are reported in Figure 3. In the highest mitigation ambition scenario (i.e. P4), changes in trade patterns and trade balances vary across sectors (right panel, Figure 3). For instance, the shift towards a healthier plant-based diet requires the EU27+2 to import more crops and grains from ROW and to slightly reduce its imports of meat and other animal foods. Moreover, the EU27+2's fossil fuel imports decrease, following its declining demand by the energy-relevant sectors (transport, manufacturing, etc.). In terms of trade volume, the more significant trade pattern changes are in the manufacturing and service sectors. With the decarbonization ambitions reducing manufacturing outputs, the EU27+2 would have to import more to make up for the shortfall to meet consumer and intermediate demands for manufacturing products. For the service sectors (excluding transportation services), increased demand arising from reallocated consumer budget towards less emission-intensive services (and away from emission-intensive products) would result in increased import demand for services. For transportation services, assumed technical enhancements in the EU27+2 would lead to an improved trade balance with ROW.

In contrast to the results from P4, when the EU27+2 reduces its mitigation efforts relative to the 2050 baseline (as in P1), we observe from the simulation results the opposite changes in the external trade balance at the sectoral level. According to the results from P1 (left panel, Figure 3), both consumers and industries would increase their demand for fossil fuels. Emission-intensive manufacturing production would go up and exceed domestic demand in the EU27+2, allowing net exports to go up. As such, in this scenario the EU27+2 would improve its trade balance with the ROW in manufacturing products but increase its net fossil fuel imports. From the consumption side, as EU27+2 consumers are expected to allocate more budget towards emission-intensive products, the EU27+2's service imports would decrease and its service exports would decrease, resulting in increased service trade balance.

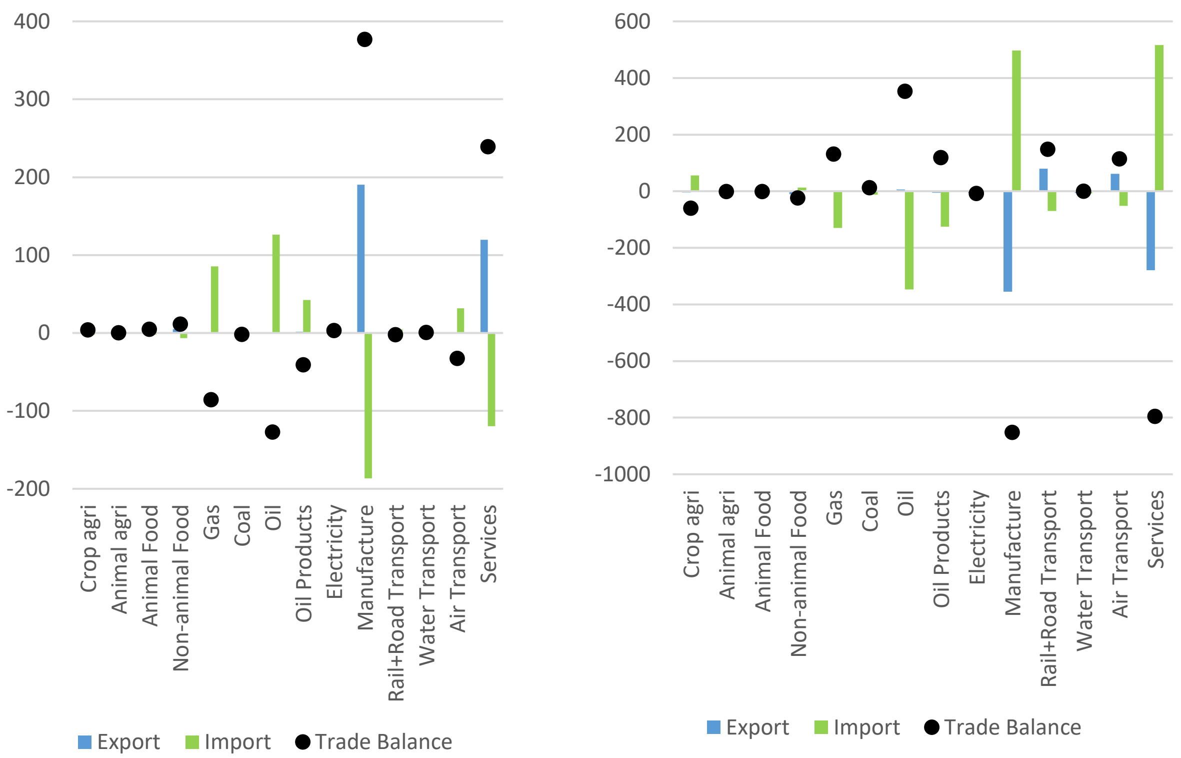

Figure 3 Change in EU's external trade by sector in P1 (left) and P4 (right), relative to baseline (bln USD)

4.2 GHG emissions, trade balance and carbon leakage

Mechanisms described for the representative scenarios P1 and P4 are similarly driving the external effects simulated from all the other scenarios considered in this study. In what follows, we summarize the aggregate external effects of all 31 scenarios simulated with GTAP-EUCalc, focusing on reductions of GHG emissions, changes in external trade balance, and carbon leakage rates, as well as the interlinkages between these effects.

We start by comparing the effects on external trade balance and reductions of GHG emissions across all scenarios, as displayed in Figure 4.[9] In general, in the absence of matching decarbonization ambitions from ROW, we observe that reductions in the EU27+2's GHG emissions generally correspond to deteriorations of its external trade balance. This is mainly because increasing mitigation ambitions on the supply side – a combination of changing technologies, altered cost structure, and efficiency improvements – lead to more constraints on the supply-side of the economy, generating higher costs and prices as compared to ROW (which is not assumed to implement climate policies in this study). This is best illustrated by the results from the scenarios with uniform ambition levels on both demand- and supply-side: while the lowest ambitions in P1 result in increasing GHG emissions and improving trade balance in the EU27+2, successively elevated ambitions in P2, P3 and P4 lead to reductions in GHG emissions and deteriorating trade balances. However, results from scenarios with uneven ambition levels across demand and supply levers – while generally display the same positive association between changes in GHG reductions and trade balance – show a more nuanced picture. Here, we focus on four groups of scenarios, each with uniform ambition settings on the demand side and varying ambition settings on the supply side.

The first group consisting of P1[1,1], P5[1,2], P6[1,3], and P7[1,4] – labeled as Group 1 in Figure 4 – has lower ambitions than the baseline on the demand-side (i.e. higher consumption; as indicated by the first number in the bracket) but increasingly higher ambitions on the supply-side (e.g. lower emissions per unit produced; indicated by the second number in the bracket). This structural mismatch between demand and supply leads to a deteriorating trade balance, as import demand intensifies while export capacity declines, compared to scenarios with similar emission reductions. For instance, pathway P7 places all the supply side levers at ambition level 4 while demand-side levers remain at ambition level 1; as such, 56% reductions of GHG emissions are reached in the EU27+2 but the EU27+2's trade balance would decrease by USD 1,303 billion. In the case of P5 and P6, smaller mismatches between demand and supply ambitions would result in smaller decrease in trade balance but also smaller GHG emission reductions. In P1, uniform ambitions across demand and supply levers at the lowest ambition level actually increase GHG emissions and trade balance, as noted earlier.

The second group, comprising of P14[4,1], P15[4,2], and P16[4,3], and P4[4,4], and labeled as such in Figure 4, place the demand-side levers at the highest ambition level (i.e. level 4), with weaker efforts on the supply-side (at levels 1, 2, 3, and 4, respectively). Major lifestyle changes in these scenarios imply drastically reduced consumption and decreased import demand for a wide range of goods and services with major emission footprints. In the case of scenario P14, where supply-side mitigations actually decrease relative to the baseline, domestic outputs increase, leading to increased net exports and improved trade balance. The net effects on GHG emissions is therefore a relatively modest reduction of 16% from the baseline level. In the cases of P15, P16, and P4 where supply-side levers are respectively set at ambition levels 2-4, net exports from the EU27+2 are reduced and trade balance lowered as compared to P14. At the same time, decarbonization measures from both the demand and supply side in P15, P16 and P4 are able to significantly

[9] To maintain consistency between the results shown, the percentage change in GHG emissions show in Figures 4 and 5 is calculated by using the GTAP-EUCalc model. Even though the relative magnitudes in respect to the lever settings are consistent with EUCalc (e.g. all levers on 4 lead to a reduction in emissions higher than all levers on 3, and so on), there are some differences. For example, carbon capture mechanisms are not explicitly modeled in GTAP-EUCalc, hence the emission reductions are lower than in EUCalc.

reduce GHG emissions, by 46%, 58% and 64%, respectively. Given the same demand-side ambitions but varying supply-side ambitions across these scenarios, it is clear that large GHG reductions can only achieved with ambitious measures from both sides. Across these two groups, it is also evident – from the relative locations of Groups 1 and 2 scenarios in Figure 4 – that ambitious lifestyle changes in the demand side can not only achieve better GHG reduction outcomes, but also help reduce the deterioration in the EU27+2's trade balance.

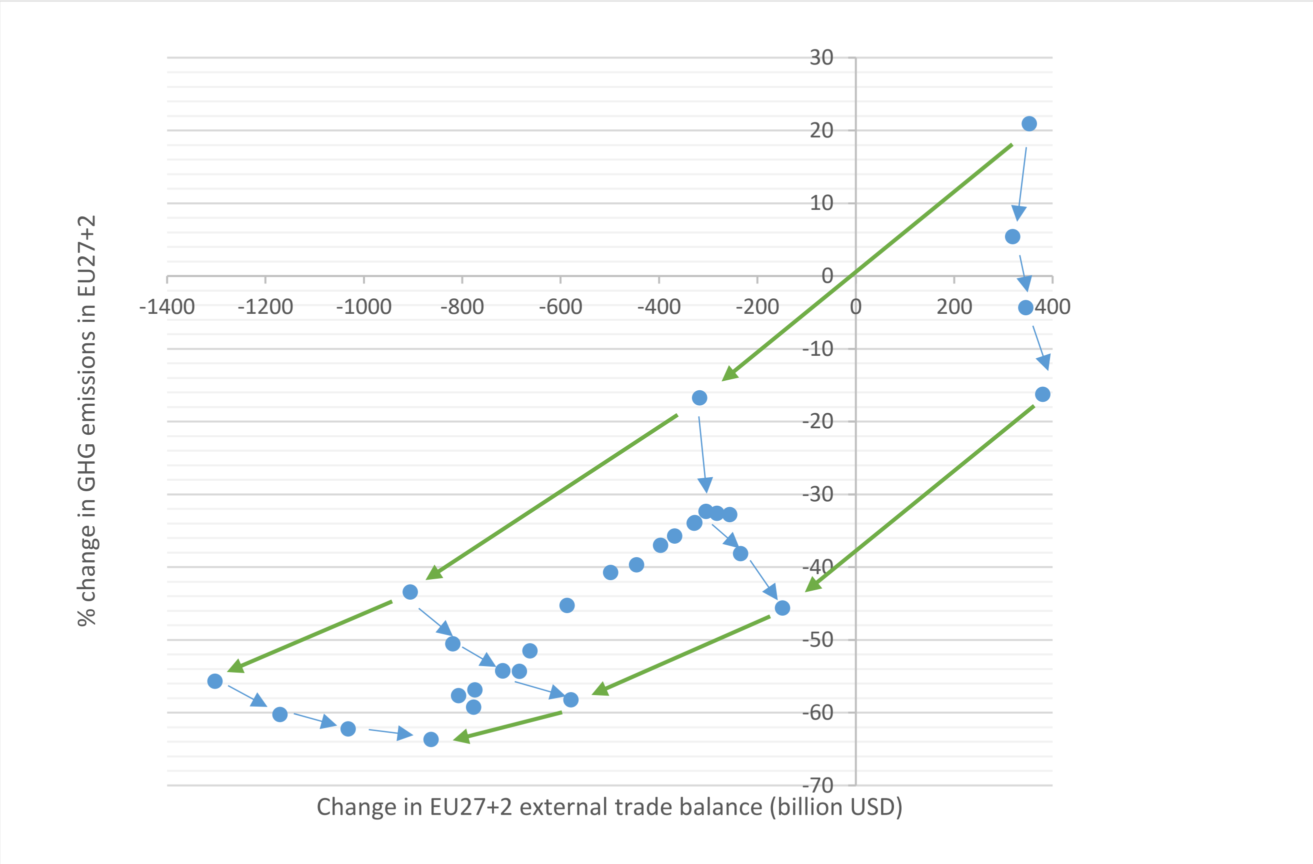

Figure 4 – Change in GHG emissions (%) and external trade balance (billion USD) in EU27+2, relative to baseline

Groups 3 and 4 contain, respectively, scenarios with the lowest and highest ambitions levels on the supply side, while allowing demand side ambitions to vary. In Group 3, which includes scenarios P1[1,1], P8[2,1], and P11[3,1], and P14[4,1], increasing trade balance are observed for all four scenarios in connection with lower-than-baseline supply-side ambitions. Increasing demand-side ambitions that reduce consumption help to reduce GHG emissions and generally improve trade balance, as expected. Likewise, in scenarios listed in Group 4 (i.e. P7[1,4], P10[2,4], and P13[3,4], and P4[4,4]) where supply-side levers are set at the most ambitious level 4 and demand-side levers are set at increasing ambition levels, similar patterns are observed: reductions in GHG increase and trade balance improves with increasing demand-side ambitions. The relative locations and "slope" of these two groups in Figure 4 are also revealing: shifting from the lowest supply-side ambition (i.e. Group 3) to the highest supply-side ambition results in drastic reductions in GHG while also worsens trade balance; when supply-side ambitions are higher, increasing demand-side ambitions results in larger improvement in trade balance.[10]

In summary, our results suggest a strong positive correlation between GHG emission reductions and trade balance changes, with more ambitious actions from both the demand and supply side delivering the most significant GHG reductions and trade balance changes. Exceptions to this general observation occur when increasing demand-side ambitions while keeping supply-side ambitions constant. In such cases, increasing demand-side ambitions further reduce GHG emissions while also improving trade balance. Furthermore, the improvement in trade balance with successively increasing demand-side ambitions is larger when supply-side ambitions are higher, as reflected in the slope of the lines connecting the scenarios in the groups shown in Figure 4.

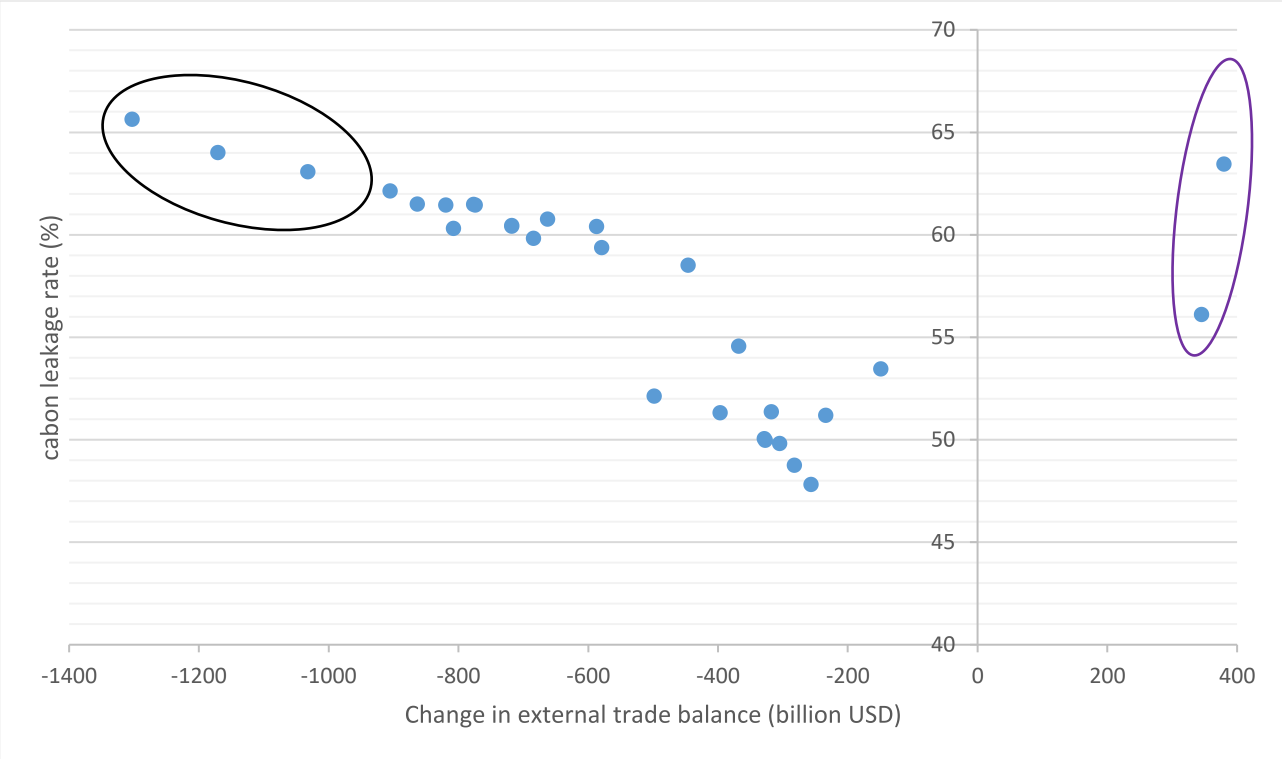

Figure 5 – Carbon leakage rates (%) and change in EU27+2's external trade balance (billion USD), relative to baseline

Next, we explore the relationship between changes in trade balance and carbon leakage from the simulation results. In Figure 5, we observe a generally negative relationship between changes in the external trade balance and carbon leakage rates (i.e. carbon leakage rate increases as trade balance deteriorates).[11]

Scenarios P10, P7, P13 (circled in black) report the largest decreases in the EU27+2's external trade balance. The simulated carbon leakage rates from these scenarios are also the highest, at 66%, 64%, and 63%, respectively. The main driver of high carbon leakage rates in these scenarios can be found in the so-called

[10] In-between Groups 3 and 4, scenarios P5[1,2], P2[2,2], P12 [3,2] and P15[4,2] can be grouped together, so as scenarios P6[1,3], P9[2,3], P3[3,3] and P16[3,4]. In both cases, as plotted in Figure 4, increasing demand-side ambitions while keeping supply-side ambitions constant increase GHG emission reductions while improving trade balance for the EU.

[11] Scenarios P1 and P8 are excluded from Figure 5, as these scenarios result in increasing GHG emissions in the EU27+2.

"competitiveness" channel (Demailly and Quirion 2006, Kuik and Hofkes 2010), as strong decarbonization ambitions on the supply-side push up costs and prices for the affected products in the EU27+2. Without matching decarbonization efforts from ROW, higher costs and prices in the EU27+2 relative to that in ROW would lead to increased production and exports from in ROW, in turn increasing production and GHG emission in ROW and partially offsetting GHG reductions in the EU27+2. Not surprisingly, the scenarios with the lowest carbon leakage rates are among the ones with lowest decrease in trade balance, such as P2, P19, P21, and P24. These scenarios typically have balanced decarbonization ambitions across all demand and supply-side levers that minimize the demand and supply imbalances within the EU27+2, resulting in small deteriorations of the EU27+2's trade balance. At the other end of the spectrum, increased trade balance is found in scenarios P11 and P14 (circled in purple in figures 5); however, carbon leakage rates are still very high in these scenarios (at 56% and 63% respectively), despite the very minor reductions of GHG emission in the EU27+2 (at -4% and -16%, respectively). The high carbon leakage can be understood by the so-called fossil fuel channel (Tan et al. 2018), where decreases in household demand for fossil fuels (e.g. for private transportation) in the EU27+2 leads to a decline in world fossil fuel prices, which in turn incentivizes increased consumption in the ROW.

Finally, of the 29 scenarios (out of 31) with decreasing EU27+2 GHG emissions, all but three scenarios report EU27+2 emission reductions between 32% (P2) and 66% (P4). At the same time, carbon leakage rates range between 48% and 66% (Figure 6), with a direct relationship between the decrease in GHG emissions and the carbon leakage rate, confirming the findings by Boeters and Bollen (2012), even though with a different modelling approach.

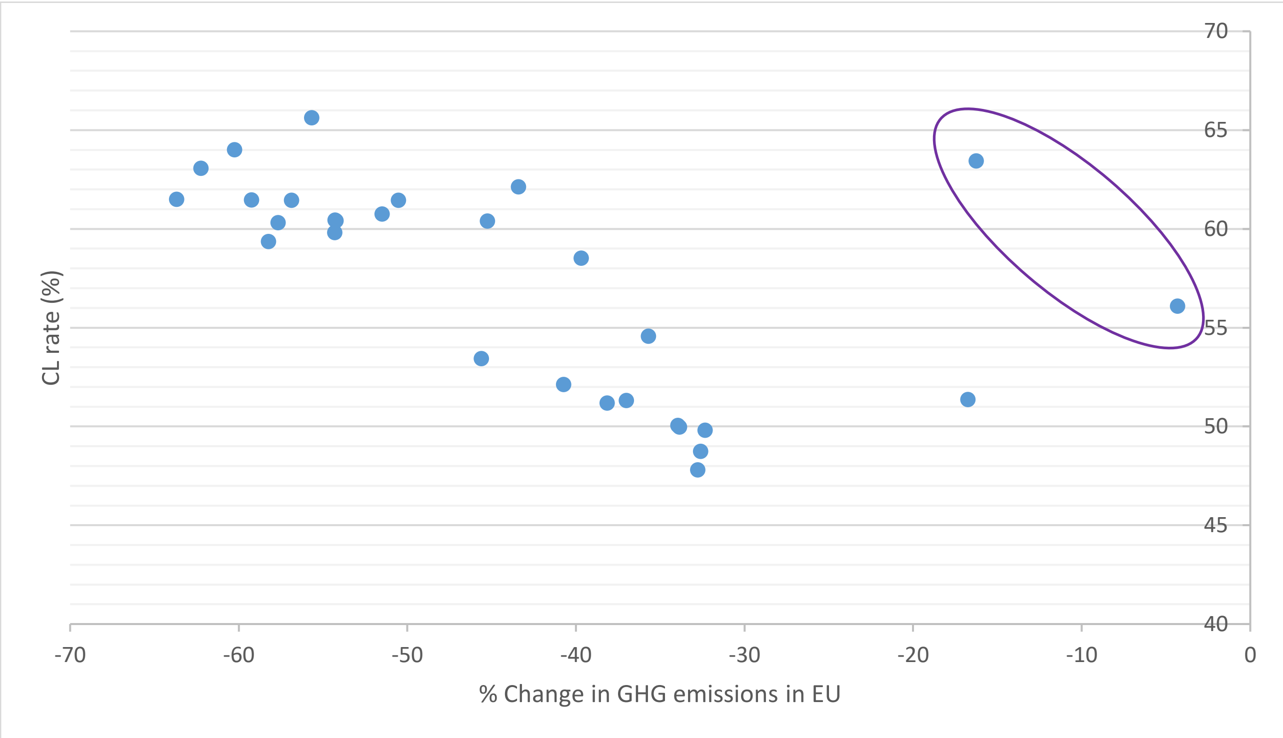

Figure 6 – Carbon leakage and change in GHG emissions in the EU27+2, relative to baseline

5. Conclusions

Deep decarbonization of the European economy calls for new lifestyle choices, a transition towards fossil-free energy systems, and structural and technological changes in GHG emission-intensive industries. In practice, decarbonization pathways of relevance to actual policy debates need to be formulated with clearly defined economy-wide and sectoral goals, taking into considerations each sector's emission footprint and abatement potential and its linkages to other sectors. In this context, a particularly valuable exercise is to gather and analyze a sufficiently large set of concrete pathways to develop in-depth understandings of the potentials and options to advance the overall and sectoral-specific decarbonization agenda and to untangle the inherent tradeoffs of these options. The methodological contribution of this study lies in the exploitation of the rich sectoral details of the EUCalc model as a source for formulating concrete and relevant decarbonization pathways for the EU, UK and Switzerland, and in the development of a tailored-made CGE for modeling these pathways and analyzing their effects. In all, 31 European decarbonization pathways are formulated and analyzed in this study.

The focus of our analysis is the external effects of decarbonizing the European economy, as changes in costs and prices of goods and services in Europe – driven by its decarbonization efforts – influence its competiveness and external trade patterns. While many countries in the rest of the world have pledged to participate in climate mitigations under the Paris Agreement, not all of them have clearly stated their overall ambitions and detailed decarbonization pathways. Given this uncertainty, it is possible that GHG emission reductions in Europe are partially offset by increased emissions elsewhere. The second contribution of the paper is therefore a systematic exploration of the linkages between GHG emission reductions, changing trade balance, and carbon leakages across a wide set of decarbonization pathways encompassing key demand and supply levers with varying ambition levels.

A set of interesting and policy-relevant results have emerged from our modeling exercises. *First*, our modeling results suggest that increasing ambitions to decarbonizing the European economy with uniform ambition levels across the demand-side and the supply-side would lead to more substantial reductions of GHG emissions in Europe (by 64% in the most ambitious scenario relative to the 2050 baseline), but at the same time decrease its external trade balance. In the absence of similar decarbonization efforts in the rest of the world, this also causes significant carbon leakage (at more than 60%) and weakens the global climate change mitigation effects of the European decarbonization efforts. Underlying this result is the improved trade balance with fossil fuel exporting countries that is outweighed by the deteriorating trade balance with China, other major Asian economies, the US, among others, from which Europe would import more emissions-intensive manufacturing products and services. *Second*, a comparison of results across scenarios with varying ambition levels between demand and supply measures further reveal their differential roles in changing Europe's GHG emissions and trade balance. When keeping demand-side ambitions constant, elevating ambitions on the supply side leads to larger emission reductions and bigger decrease in trade balance; however, holding supply-side ambitions unchanged and increasing demand-side ambitions improves trade balance (i.e. smaller losses of net exports) while achieving larger emission reductions. In particular, the effects of more ambitious demand measures on lowering losses of net exports are stronger when they are coupled with more ambitious supply mitigation measures. Together, these two sets of results illustrate the need to coordinate the demand and supply mitigation actions across sectors for achieving ambitions emission reductions in Europe. At the same time, given the likely differential adjustments to Europe's external trade pattern across sectors and trading partners, appropriate domestic policy should be installed to facilitate these adjustments. Furthermore, the results point to the benefits of climate-friendly lifestyle choices in not only reducing emissions but also in avoiding undesirable trade outcomes. Therefore, it is importance to balance the demand and supply measures and to consider more ambitious actions particularly from the demand side in designing European decarbonization strategies.

Third, our results also demonstrate the positive associations between worsening trade balance and rising carbon leakage rate, and between increasing reductions in European GHG emission and rising carbon leakage rates. Therefore, as a first-best policy response to the dilemma between emission reduction and shrinking competitiveness, it is imperative for the EU, the UK and Switzerland to actively engage the rest of the world for joining the global decarbonization efforts. In the absence of active global cooperation, other policy instruments are suggested. For instance, trade policy options such as border carbon adjustment have been suggested (Antimiani et al. 2013, Fischer and Fox 2012, Böhringer, Balistreri, and Rutherford 2012) as possible remedies. However, the application of such remedies should be carefully evaluated regarding their efficacy in incentivizing other countries to commit to similar climate change mitigation efforts, particularly in the current environment where global cooperation seems to be quite fragile, in addition to political, legal and design challenges (Cosbey et al. 2019). Furthermore, even without carbon leakage, decarbonization efforts by Europe alone are unlikely to reduce global emission effectively as the European share of global economy and GHG emissions are expected to fall further towards 2050. Therefore, concerted actions at the global level – for example under the auspice of the Paris Agreement – are needed to realize global GHG reductions consistent with the 1.5 degrees goal. We conclude that there is an urgent need to carefully balance potentially conflicting policy options for supporting decarbonization efforts in Europe, safeguarding national industries under transition, and incentivizing the rest of world to join the worldwide decarbonization efforts.

The magnitude of carbon leakage rates obtained in our study appear to be at the higher end of available estimates, possibly due to a combination of reasons. For instance, emission reduction targets in this study are more ambitious than earlier research (Branger and Quirion 2014, Carbone and Rivers 2017). In fact, previous studies (Boeters and Bollen 2012, Carbone and Rivers 2017) have identified a direct relationship between carbon leakage rate and emissions abatement target, a point that has been also clearly supported by our numerical results across the different scenarios. A second reason is that Europe's shares of global GDP and GHG emissions are widely projected to decrease by 2050, thereby implying higher carbon leakage rates in connection with the European decarbonization action. This point has also been suggested by Botteon and Carraro (1997), Branger and Quirion (2014) and Böhringer, Fischer, and Rosendahl (2014). Thirdly, the sectoral approach in building the decarbonization pathways from the EUCalc model, while rich in technical details, possibly implies more structural mismatches between demand and supply as well as across sectors that elicit larger adjustments on domestic and international markets, as compared to the implementation of a uniform carbon pricing across countries (Paltsev 2001). Fourth, the inclusion of non-CO2 emissions can trigger additional leakage effects when mixed with cost-inefficient decarbonization scenarios (Bednar-Friedl et al. 2012). Last but not the least, no technological spillovers from the Europe to the rest of the world (Gerlagh and Kuik 2014) and no climate policies in the rest of the world are taken into account in this study, with both being shown to reduce carbon leakage rates.

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