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Climate action, environment, resource
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COP21 RIPPLES

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1. **Changes with respect to the DoA**

DSGE MEWA model was used to assess the importance of endogenous technological change for the industrial competitiveness in the EU rather than the intra-EU heterogeneity. This has allowed to better complement the results of CGE ICES model, which provides detailed results of differences in competitiveness impacts both within the EU and between European countries and the rest of the world but does not explicitly model endogenous technological change (i.e. decisions of companies to invest in R&D in response to market and policy drivers). This change has allowed the authors to address the research questions within this the task more comprehensively.

2. **Dissemination and uptake**

Within the project: all tasks in Work Package 3
Outside the project: This study provided insights for the policy brief "Heterogeneity in the EU low-carbon transition" and the upcoming deliverable D2.5 to syntheses the adequacy assessment of the COP21 outcome. The scenarios underlying the analysis belong to the COP21 RIPPLES Scenario Database (D2.1). The research findings should be able to inform the EU discussion on the industrial roadmap and the 2050 EU target. The research report is going to be disseminated through the Consortium's research networks and websites.

3. **Short Summary of results (<250 words)**

This deliverable presents an analysis of trade and competitiveness indicators at the sectoral level focused on energy intensive sectors in Europe, with particular focus on interactions between climate policies compliant with the Paris Agreement long-term goals and various measures supporting industrial competitiveness. The analysis of decarbonisation scenarios takes into account policy options to address competitiveness concerns as well as industrial policies in a climate policy context, including those focusing on technological progress and diffusion as well as international cooperation in the form of climate clubs. The first part of the analysis relies on a recursive dynamic multi-region and multi-sector CGE model enhanced with import driven technology spillovers, considering three decarbonisation elements: energy efficiency improvements, the deployment of electricity as the main source of energy, and the decarbonisation of the power generation system. These elements vary in intensity for each decarbonisation scenario reflecting the level of ambition in curbing emissions by 2050. All indicators are calculated for three decarbonisation scenarios and results are presented at the European level as well as by countries for seven industries including a brief analysis of industrial policies in a climate policy context. In the second part of this report (last chapter), the analysis based on CGE modelling is complemented by the results of DSGE model simulations with endogenous technological change. Six scenarios are considered with different climate policy settings (equal global effort, diversified global effort) and variants on the availability of low-carbon R&D investment options (no R&D, only private R&D, private R&D with public support).

4. **Evidence of accomplishment**

This deliverable

D3.4 REPORT ON COMPETITIVENESS, TRADE, AND INDUSTRIAL IMPLICATIONS OF THE INDCS AND 2°C /1.5°C MITIGATION PATHWAYS

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1 Introduction

This report assesses the implications of the NDCs and 2°C/1.5°C pathways on international trade, technological progress and diffusion, and industrial competitiveness with a specific focus on energy intensive trade exposed (EITE) sectors.[1] Literature has mostly focused on unilateral climate policy assessments with concerns about its effectiveness due to carbon leakage increasing emissions in regions without climate policy as well as concerns about loss of competitiveness of industries that should comply with the unilateral policy against industries facing no constraint at all (De Cian et al., 2017). The assessments of pathways with a long-term goal to keep global temperature rise below a certain threshold are based on a global cap on emissions based on a multilateral climate policy, and therefore, concerns on the policy effectiveness (or carbon leakage) are ruled out of the analysis. However, concerns about competitive loss for some industries are still amongst the most important issues in the climate policy debate.

While concerns about policy effectiveness and carbon leakage might have lost terrain in the recent global context in which most of the world has signed the Paris Agreement (PA) and countries have submitted their National Determined Contributions (NDCs), the potential effects on trade and competitiveness are still an important part of the debate. The PA represents a step forward to a coordinated multilateral climate policy with a long-term goal and the formulation of NDCs which, although non-binding, should be revised periodically. However, the agreement does not fully address competitiveness concerns since the NDCs are not a coordinated set of targets, but rather they are co-incidental (Hermwille et al. 2018). At the same time, this framework could create new opportunities for initiatives focused on fostering international cooperation, supporting technological progress and diffusion of low-carbon innovations.

The analysis involved the identification of specific trade and competitiveness indicators from the literature and the use of two complementary general equilibrium models to provide quantitative assessment of their evolution under various climate and industrial policy scenarios. The two models are: 1) A multi-sector and multi-region Computable General Equilibrium (CGE) model enhanced with import driven technology spillovers, which takes into account international trade flows, and 2) A large-scale multi-sector Dynamic Stochastic General Equilibrium (DSGE) model with endogenous technological change (i.e. ability of companies to invest in R&D in response to market and policy incentives).

The structure of the report is organised as follows. This introduction presents a discussion that frames competitiveness concerns in the current international policy context, considering findings of the literature on the topic, the available policy options to address competitiveness concerns, and discussing the caveats and limitations of the CGE framework. The selection of trade and competitiveness indicators is presented in section 2, while section 3 describes the CGE model used in this report. Section 4 introduces the main assumptions of the decarbonisation scenarios analysed while section 5 offers an analysis of competitiveness and industrial policies in a climate policy context. Section 6 presents the

[1] EITE sectors in this study are Non-Metallic Minerals, Iron & Steel, Chemicals, Non-Ferrous Metals, and Paper and Pulp.

results on competitiveness and international trade of three decarbonisation scenarios for the European Union (EU) as an aggregate, for selected EU countries and for seven selected industries. Section 7 presents the results of DSGE modelling focused on the links between endogenous technological change and competitiveness impacts of decarbonisation scenarios in the EU. Finally, section 8 concludes.

1.1 Competitiveness in a context of heterogeneous climate policy

After the entry into force of the PA there is a new international climate policy context where countries should comply with their voluntary NDCs by means of several policies. Moreover, this new context implies that all countries in the world must reduce emissions to achieve the long-term goal of 1.5°C or less than 2°C. While in the past the concerns about the effectiveness of climate policy were directly related with competitiveness and carbon leakage due to the implementation of unilateral climate policies, nowadays most of the world has acknowledged the need to reduce global warming which would set a new multilateral climate policy background with the common target of reducing greenhouse gas emissions. Nevertheless, concerns about the competitiveness of specific energy intensive industries are still worth considering in a world where differentiated mitigation efforts will exist in several countries and coalitions, in particular in a context of international competition. In fact, a Working Paper of the High Level Commission on Carbon Pricing and Competitiveness acknowledges that competitiveness issues should be continually monitored even though “As more and more countries adopt climate policies in line with the Paris Agreement, competitiveness issues should become less of an issue and EITE protections can potentially be relaxed.” (CPLC, 2018).

The concept of carbon leakage has been closely related with competitiveness in the discussion of unilateral climate policies (Aldy, 2017; Bohringher and Alexeeva-Talebi, 2013; De Cian et al., 2017) as a concern where a country or a coalition of countries putting a cap on emissions would incur in additional costs while the rest of the world would not face similar constraints nor costs. However, the current climate policy debate has been gradually evolving to a setting where implementing low carbon policies has become part of national development priorities essential to address global warming and that these policies should be enforced by all countries in the world with no exception.

The effects on competitiveness remain a fundamental issue to understand and address in order to reap the benefits (or offset the costs) of a transition to a low carbon economy and, at the same time, to take the necessary measures to protect and foster the development of clean and low carbon industries. Some of these concerns are based on energy price increases derived from climate policy, although the carbon cost component is still very low (van Renssen, 2014). However, this may change if raising the ambition to mitigate emissions would require a higher carbon price. These concerns have been raised mainly by developed countries’ industries, but rising energy prices due to climate policy effects could have higher macroeconomic effects in developing countries and their industries (Bataille et al. 2018a). However, before this new backdrop where many countries have pledged mitigation efforts, the concerns about competitiveness of industries within countries implementing such efforts need to be assessed and addressed in a different way from the past, where only a handful of countries were committed to fight climate change. The current climate policy (based on a bottom-up architecture) implies that for many years to come countries will face different mitigation challenges depending on

their idiosyncratic features with international consequences, which will lead to the consideration of additional policy measures to address competitiveness concerns.

These new mitigation efforts could also change the international context in which trade and climate regimes have co-existed without harsh disputes. However, the interaction between the trade and climate policy fields could increase (Droege et al., 2017). Complying with the PA long-term goals will demand the use of trade instruments to deal with competitiveness concerns and this will call for a close cooperation between trade and policy regimes. For an assessment of the interaction between the climate policy measures with the WTO trade regime including regional trade agreements see Droege et al. (2017) providing an overview of the two regimes while considering the legal and political dimensions as well as focusing on what elements of the international trade regime could support mitigation policy efforts.

1.2 Competitiveness and international trade concerns in the literature

Concerns about climate and environmental policy impacts on competitiveness and their close relation with carbon leakage have been analysed in the past by several studies. Deliverable D3.1 of the COP21-RIPPLES project (De Cian et al., 2017) summarises this issue focusing on competitiveness, carbon leakage and the EU policy options in the post- Paris Agreement landscape. The existing literature is recapped also by reviews focusing on ex-post studies (Dechezleprêtre and Sato, 2014, Arlinghaus 2015) and also on ex-ante analyses (Carbone and Rivers 2017). All reviews coincide in the importance of defining the term competitiveness[2] and indicating that it relates to a firm or sectoral level, arguing that it would be difficult to analyse competitiveness at the country level. On one side, ex-post studies do not find evidence on competitiveness effects and attribute this to a lack of stringency of policies, the implementation of additional measure to reduce those effects, and/or lack of data for a proper analysis of a complex phenomenon. On the other side, ex-ante studies find higher effects, and this would be the result of analysing scenarios with more stringent mitigation policies than ex-post studies.

Dechezlepretre and Sato (2014) review (more than 80) ex-post evaluation studies about the impacts of environmental regulations on competitiveness focusing on productivity, employment, trade, industry location and innovation. Empirical assessments about competitiveness impacts of environmental regulations look for some kind of variation in the stringency of regulation between firms, sectors, regions or countries. However, analysing the relative stringency of such regulations have proven to be difficult for different reasons from the lack of data to the complexity of identifying proper indicators and methods to measure either the regulation itself or the impacts on competitiveness. The discussion of the existing literature in Dechezlepretre and Sato (2014) follows six main issues:

[2] "Competitiveness at the sector level refers to how attractive different countries are for a particular industry and is often measured in terms of performance in international trade (net exports, investment flows)" (Dechezlepretre and Sato 2014).

1) The costs of environmental regulations represent a small share of the production value for most activities, but they could increase entry and investment costs; although the design and implementation of regulations have also considered the possible negative effects on the industry which may have lessened those adverse impacts.
2) There seems to be short-run negative impacts on productivity, while in the longer run these seem to be smaller or may be even positive.
3) Regarding employment, environmental regulations would induce insignificant effects on employment on regulated sectors that in the end suggest a substitution effect with workers moving from polluting to clean sectors during a transition period. The costs of this transition depend on the imperfections of the labour market and the policies that could be implemented to help and safeguard workers.
4) There is mixed evidence about the relocation of polluting activities to lax or non-regulating countries. This is because of the challenges to test this issue since the implicit difficulties in measuring the effect on competitiveness and the lack of appropriate measures of relative stringency of regulations.
5) Environmental regulations induce innovation in clean technologies, and therefore, can provide support for a transition to a clean development.
6) These innovations could not only improve regulated companies to become more competitive, but also could benefit unregulated ones thanks to the new knowledge available fruit of innovation that may spill over to the rest of the economy.

Carbone and Rivers (2017) also emphasize the fact that competitiveness is related to individual firms or sectors. In addition, they distinguish the determinants of competitiveness (quality of production factors and of institutions, technology, policy measures, etc.) from competitiveness outcomes (such as exports, production, employment, etc.). Their review focuses on studies using CGE models for the analysis of competitiveness outcomes at sectoral level for EITE industries under unilateral carbon regulations and find that output, exports, and employment would decrease. They identify many indicators that have been used in the CGE literature to analyse competitiveness concerns including exports, imports, output, employment, as well as the world market share of a specific sector, among others.

1.3 Summary of policy options to address competitiveness

There are several options available to reduce the adverse effects of climate policies on EITE industries facing a carbon price. These can be classified in three categories which have been discussed in detail in Droege et al., (2009) and Decian et al. (2017) and are summarised below:

1. **Adjusting carbon costs downwards for domestic firms:** These options seek to reduce carbon-related costs by maintaining a marginal abatement incentive equivalent to that if such measures are not introduced.
    a. ***Free allocation of tradable permits***: Under an Emission Trading System (ETS) this option relieves firms from buying the emission permit but maintains the incentive to abate emissions.

b. ***Output based rebates***: This option returns the revenues generated by a carbon tax to industries in proportion to their output.
c. ***Investment support***: In this case, revenues from the carbon tax are used to support investments which will reduce the cost of new, low carbon, or more efficient capital.
d. ***Environmental tax reforms***: The main idea is to shift the target of taxation from labour or capital to polluting activities.

2. **Adjusting carbon costs upwards for non-domestic firms**: These alternatives seek increasing the carbon costs of firms outside the carbon price policy.
   a. ***Sectoral agreements***: aiming to extend the participation of sectors or industries in climate mitigation efforts by offering options such as technology transfers, research and development collaboration, coordinated policies, etc.

3. **Adjusting carbon costs at the border:** These are instruments that basically adjust the carbon costs at the border of the jurisdiction implementing the carbon price.
   a. ***Border carbon adjustments***: To equalise the carbon costs on imports and exports in the jurisdiction implementing the carbon price, this option contemplates imposing the same carbon price on imports from non-regulated countries and/or rebating the carbon costs to exports to non-regulated countries.
   b. ***Consumption-based pricing***: This implies a carbon price levied on the consumption of goods regardless of their origin.

Each one of these options have different levels of political, administrative and legal feasibility as summarised in Table 1 taken from Decian et al. (2017).

Table 1: Feasibility of carbon leakage protection measures

	Political feasibility	*Administrative feasibility*	*Legal feasibility*
Free allocation of permits	High	High	High
Output-based rebates	Medium	Medium	Medium
Investment support	Low	Medium	Medium
Environmental tax reform	Low	High	High
Sectoral agreements	Low	Low	High
Border carbon Adjustments	Low	Medium	Medium
Consumption-based pricing	Medium	Medium	High

Source: Decian et al. (2017)

Free allocation is the alternative with higher political, administrative, and legal feasibility but it could have perverse effects such as over allocation of permits and windfall profits. Although there are some mechanisms to avoid these effects, they could affect the effectiveness of the policy (see Droege et al., 2009 and Decian et al., 2017). Output Based Rebates (OBR) have a medium political, administrative and legal feasibility and is similar as a production subsidy which could be challenged under the World Trade Organization (WTO) law. Consumption-based pricing has medium political and administrative feasibility and a high legal feasibility. This option may have similar administrative and political issues as BCAs but given that it would be applied uniformly to the consumption of goods it could be easier to implement.

Border Carbon Adjustments (BCA), despite having a low political feasibility, have a medium administrative and legal feasibility. The main challenges for BCAs would be administrative in order to implement them and setting the scope of participating products and firms (Grubb *et al*, 2015; Decian et al., 2017, Cosbey et al., 2019). The rest of the alternatives listed in Table 1 have a low political acceptability and the most feasible to implement would be an environmental tax reform, followed by investment support and sectoral agreements.

1.4 Analysing competitiveness in a general equilibrium framework

Multi-sector and multi-region CGE models offer a thorough description of an economy with a sectoral and regional breakdown. In addition, CGE models can be used to run counterfactual and policy scenarios providing information on indicators associated with competitiveness such as sectoral production, exports, and imports (Carbone and Rivers 2017). While CGE models may lack a comprehensive energy description system, they offer more exhaustive information on intersectoral and international flows. Moreover, the general equilibrium framework is based on market clearing conditions stating that demand must equal supply and that this is achieved by adjusting prices. Therefore, one of the most important characteristics of CGE modes is that they have built-in price signals which are propagated throughout the economic system. When considering the competitiveness effects of climate policies, these policies will mainly try to influence behaviour by increasing prices associated to polluting goods. For example, a policy implementing a carbon price will increase the cost of fossil fuels and this will be incorporated in the cost structure of other commodities using fossil fuels. This will also become an incentive to reduce emissions and foster innovation for developing low carbon and abatement technologies. The direct effect of this is that fossil fuels will become relatively less competitive compared to other sources of energy and the indirect effect is that carbon intensive goods will also have to adjust their prices to accommodate higher carbon costs. This could make that some industries (or firms) become less competitive compared to the similar industries (or firms) either because the latter use low carbon energy sources, or because they are not subject to the climate policy.

The representation of the production process in a CGE framework usually follows a similar structure for each sector. While this may be considered a limitation against partial equilibrium models able to include the specific characteristics of an industry, it is the particular structure of the data used for each sector in the CGE model that provides a representation of such characteristics. In other words, even though the theoretical formulation of the production process is the same for all sectors in a CGE model, the sector- and country- specific characteristics of an industry are considered by relying on data from National Accounts used to build the CGE models' database. In this way it is possible to keep track of the differences across sectors within a country as well as across countries within an industry.

Sacrificing the more detailed description of a sector or industry at the national level allows considering this kind of information for several countries at the same time allowing for the possibility to include international trade in the CGE model. The Global Trade Analysis Project (GTAP) is a very good example of this since it provides the research community with a database (Aguiar et al, 2017) for 57 economic sector and 140 regions on a regular basis. This database represents the world economy and has been used for different purposes including international trade agreement studies and climate change impact and policy assessments.

Another limitation of the multi-sector and multi-region CGE framework is that, since it relies on aggregated data and a parsimonious theoretical representation of the production processes, it is not able to represent specific endogenous technological progress within an industry unless it is modified with additional data. While there are some examples of this at the national level (Otto and Löschel, 2009, Otto et al., 2007; Goulder and Schneider, 1999) there are few models that include innovation and endogenous technological change in a multi-sector and multi-region setup. However, this may be overcome by making explicit assumptions on the trend of exogenous technical change and by changing the values of some substitution elasticities that represent and govern the technology options in a CGE model.

Multi-sector and multi-region CGE models provide information on intersectoral and international trade flows as well as production, so they become a useful source of information for analysing different kind of policies in an economy-wide consistent context. Carbone and Rivers (2017) in their review of CGE studies focus on competitiveness outcomes at sectoral level for EITE sectors and cite the following examples of variables that have been used in the modelling literature:

- Exports (proxy measure of competitiveness on the international market)
- Imports (proxy measure of competitiveness on the domestic market)
- Net exports (proxy measure of competitiveness on the domestic and international market)
- Revealed Comparative Advantage (RCA) as the ratio of export value over import value of a specific sector over the ratio of aggregate export over aggregate imports
- Changes in relative world trade share
- Market share of the domestic sector in the domestic market
- Cost of domestic output/world price

2 Trade and competitiveness indicators

For this deliverable we drew on the existing literature and selected the following indicators which could be used in a CGE framework to provide insights about the effects on competitiveness of climate policy implementation aiming at a low carbon economy in line with the goals of the Paris Agreement.

Exports market share (MS): Defined as the ratio between exports of commodity *i* by region *r* ($X_{i,r}$) over world exports of commodity *i*, representing the contribution of an exporting country to the world export market.

$$MS_{i,r} = \frac{X_{i,r}}{\sum_r X_{i,r}}$$

This is a straightforward indicator with the advantage of showing the importance of an industry within world exports. However, given that the contribution of each sector is normalized to total world exports it would tend to favour larger industries, but this bias could be controlled when looking at shifts in the market share since they would reflect changes in competitiveness compared to a reference case besides to other countries exports (Vollrath, 1989).

Net exports to output ratio (NXY): This indicator compares the trade balance (exports – imports) as a ratio of the domestic production of a commodity.

$$NXY_{i,r} = \frac{X_{i,r} - M_{i,r}}{Y_{i,r}}$$

Where M_{ir} are imports of commodity *i* by country *r*, and $Y_{i,r}$ is commodity *i* output produced by country *r*. Compared to the market share, this indicator includes also the flow of imports to show the net position of the country in international trade. The advantage of this indicator is that the trade balance of a commodity shows if the country is a net exporter (importer), and by comparing the net trade balance with the domestic production in the country, it shows how important is the trade balance in terms of output. This kind of indicator is complementary to the market share since it looks at exports and imports related to production levels and within a country, while the market share takes into account the relative importance considering the rest of the world.

Revealed comparative advantage RCA1 (Exports):[3] This indicator is a measure of trade specialization with the term coined by Balassa (1965). Basically, it compares the share of exports of a commodity over total exports in a country with the same concept at the world level (i.e. the share of world exports of a commodity over total world exports). Bohringer an Alexeeva-Talebi (2013) refer to this measure as a relative world trade share.

$$RCA1_{i,r} = \frac{X_{i,r} / \sum_j X_{j,r}}{\sum_s X_{i,s} / \sum_j \sum_s X_{j,s}}$$

This indicator extends the concept of the market share and can be interpreted in two forms. The first one refers to the share of exports of a commodity within a country compared to the world average as described above. The second interpretation following Bohringer and Alexeeva-Talebi (2013), is obtained by exchanging the denominators of each share so the comparison is between "...the ratio of a country's exports in a certain sector to the world's exports in this sector with the ratio of a country's overall exports to the world's exports in all sectors." In any case both interpretations point out the outcome of the sector in a country compared to the world average. However, being an indicator based on market shares of exports, its validity has been questioned for not considering import flows Bohringer an Alexeeva-Talebi (2013).

If the value is higher than 1 then it is said that there is a revealed comparative advantage. For the purposes of this report this indicator will be represented in all figures as the natural logarithm of is value, *Ln(RCA1)*, with a positive value indicating that there is a comparative advantage while values lower or equal to 0 indicates a comparative disadvantage.

[3] This is the same concept used in Chapter 1 of Deliverable D3.3 of the COP21-RIPPLES project

Revealed comparative advantage RCA2 (Exports/Imports): A variation of the *RCA1* indicator, also proposed by Balassa (1965), that compares the ratio of exports to imports of a commodity and the ratio of total exports to total imports of a country. We include this indicator since it is a measure of competitiveness of industries within an economy (Bohringer an Alexeeva-Talebi, 2013).

$$RCA2_{i,r} = \frac{X_{i,r}/M_{i,r}}{\sum_j X_{j,r}/\sum_j M_{j,r}}$$

The advantage of this indicator is that it takes into account both imports and exports at the same time by comparing first exports against imports within a sector and then compare this ratio to the world average.

Similarly to the case of *RCA1*, a value higher than 1 indicates a revealed comparative advantage, and for presentation purposes it will be represented as the natural logarithm of is value, *Ln(RCA2)*, with a positive value indicating a comparative advantage while values lower or equal to 0 indicates a comparative disadvantage.

World Price to Export Price Ratio (WPXPR): Information about price levels is usually not available in a CGE framework. However, it is possible to use price indices to calculate a ratio between the world price index of a commodity and its export price for a specific country. In a the CGE framework export prices are determined when supply and demand are cleared at the market, and besides that, it is also possible to calculate a global price of a commodity.

This ratio shows the behaviour of one of the drivers of competitiveness, namely export prices compared to the world price average. If a commodity export price is below the world price, then it is more competitive given that a lower price would foster more exports of that commodity. While this is true when considering price levels, by comparing the ratio of price indexes it is possible to show the evolution of the world price-exports price gap.

$$WPXPR_{i,r} = \frac{WPI_i}{XPI_{i,r}}$$

Where WPI_i is the world price of commodity *i* and $XPI_{i,r}$ is the export price of commodity *i* in country *r*. Therefore, if the ratio increases it means that export prices have grown at a slower rate compared to the world price and this would imply a relative improvement of exports comparative advantage.

The following three measures have been proposed as alternatives to the indicators proposed by Balassa and are indicators based on the concept of revealed competitive advantage (Vollrath 1991). These indicators distinguish "between a specific commodity and all other commodities and between a specific country and the rest of the world" (Vollrath, 1991). In their essence, Vollrath's indicators show the importance of trade flows of a specific commodity by comparing them to flows of the rest of the commodities, and by applying this concept first within a country and then comparing it to trade flows from the rest of the world in a similar way. The advantage of this methodology is that it can focus on

exports and imports separately and then use both indicators to formulate a Revealed Competitiveness indicator.

Relative Export Advantage (RXA): The advantage of an exporting sector is revealed in this indicator by comparing two ratios. The first one is the ratio of exports of commodity *i* to exports of all commodities but commodity *i* in country *r*, while the second one is the ratio of exports of commodity *i* to exports of all commodities but *i* in the rest of the world (Vollrath 1989, 1991)

$$RXA_{i,r} = \frac{X_{i,r} / X_{n,r}}{X_{i,m} / X_{n,m}}$$

Where subscript *n* refers to all traded commodities minus commodity *i*, and subscript *m* refers to all the world minus region *r*. This indicator shows the importance of a sector compared to the rest of the economy both at the country and world levels. Therefore, if in the first ratio exports of a commodity have a higher value in country *r*, its value will be higher than the share of exports in the economy given that the denominator excludes those exports.

Relative Import Advantage (RMA): Defined in an analogous way for imports, this indicator emphasizes the import advantage of commodity *i* in country *r* compared to the rest of the world and the rest of imported commodities (Vollrath, 1991).

$$RMA_{i,r} = \frac{M_{i,r} / M_{n,r}}{M_{i,m} / M_{n,m}}$$

Revealed Competitiveness (RC): By comparing the relative export and import advantages of a specific sector, Vollrath (1989, 1991) proposes an alternative to the revealed comparative advantage with a revealed competitiveness index that takes the difference between the natural logarithms of *RXA* and *RMA*.

$$RC_{i,r} = Ln[RXA_{i,r}] - Ln[RMA_{i,r}]$$

If RC is positive there is a comparative advantage in sector *i* that is revealed by the difference between relative export and relative import advantages for commodity *i* in country *r*. This indicator summarises the position of a commodity taking into account both export and import flows as well as they relative position compared to the rest of the other commodities and the rest of the world. In addition, as Vollrath (1991) indicates, it would be better suited at high levels of aggregation since it is sensitive to small values. In the case of small trade flows the alternative would be to calculate the difference between RXA and RMA without the natural logarithms.

From the list of indicators presented in this section, this deliverable will focus on results of two main indicators: The Relative Competitiveness (*RC*), and the Market Share *MS* () of exports. This choice is made since both indicators are complementary. While the RC indicator shows the performance of an industry independently of the size of the industry or the country, the MS indicator shows also the

importance of the industry compared to rest of the world. Although the MS might be biased to larger industries the analysis will also focus on changes with respect a base year (2011) for different scenarios in order to control for this aspect. For the sake of completeness, the rest of the indicators are presented in Appendix A for each selected industry.

3 The ICES model

ICES (Inter-temporal Computable Equilibrium System) is a top-down recursive-dynamic multi-sector and multi-region CGE model based on the GTAP model (Hertel, 1997) and the GTAP-E framework (Burniaux and Truong, 2002) using the GTAP 9a Power database (Peters, 2016, Aguiar et at, 2016). The model has been enhanced with technology spillovers embodied in Machinery and Equipment imports. This formulation is based on the fact that the use of new equipment in manufacturing and industrial sectors is a source of technological progress, and that imports of capital goods such as machinery and equipment increase the productivity of energy and capital through energy and capital-biased technical change (Parrado and Decian, 2014).

Table 2: ICES regional and sectoral aggregation

Region Code	***Region description***	***Sectors***	****Energy sectors***
Italy	*Italy*	Agriculture	Coal
France	*France*	Forestry	Oil
Germany	*Germany*	Fishing	Gas
UK	*UK*	Energy*	Oil and Coal Products
Spain	*Spain*	Mining	Transmission and Distribution
RestofEU15+	*Rest of EU15*	Food	Electricity (Nuclear)
RestofEU28++	*Rest of EU28*	Textiles	Electricity (Renewables)
USA	USA	Lumber	Electricity (Other)
Japan	Japan	Paper & Pulp	Electricity (CCS)
China	China	Chemicals	
India	India	Non- Metallic Minerals	
Brazil	Brazil	Iron & Steel	
Russia	Russia	Non- Ferrous Minerals	
SouthAfrica	South Africa	Metal Mechanics	
RoFSU	Rest of Former Soviet Union	Vehicles	
MDE	Middle East	Machinery & Equipment	
NAF	North Africa	Other Industries	
SSA	Sub-Saharan Africa	Construction	
SASIA	South Asia	Other Transport	
EASIA	East Asia	Water Transport	
Oceania	Australia and New Zealand	Air Transport	
LACA	Latin America & Caribbean	Services	
RoW	Rest of the World	Public Services	

+ *RestofEU15*: Austria, Belgium, Denmark, Finland, Greece, Italy, Ireland, Luxemburg, Netherlands, Portugal, Sweden
++ *RestofEU28*: Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, Slovenia, Bulgaria, Croatia, and Romania.

The characteristics of the ICES model (extensive sectoral structure and linkages between economic activities, energy use, and CO2 emissions) make it possible to study combinations of climate and trade policies, as well as to examine how their interactions can affect growth, competitiveness, and trade

using a cross-sectoral perspective. The simulation period is 2011-2050 resolved in five-year time steps from 2015 on, with 2011 as the calibration year. All simulation results are expressed in 2011 US$. Compared to the standard GTAP database and model, in addition to the dynamics in capital stock accumulation, it includes renewable energy production and carbon capture and sequestration in power generation. A more detailed description of the model is available in Appendix B. For this analysis, the world economic system has been represented in 25 regions and 19 representative industries (see Table 2) and the detail of the regional definition is available in Appendix C.

4 Decarbonisation scenarios

The transition to a low carbon economy in the scenarios simulated with the ICES model is based on the implementation of the following three decarbonisation pillars based on the Deep Decarbonisation Pathways Project (DDPP, 2015):

Energy efficiency: For energy efficiency, ICES represents autonomous improvements in energy intensity by assuming exogenous trends for energy productivity. These energy efficiency improvements increase at a slightly higher rate after 2030 and are higher in developing countries. In addition, reductions in energy intensity are facilitated by a higher substitutability between capital and energy, simulating the renovation and/or introduction of more energy-efficient capital. This has been implemented by gradually increasing the capital energy substitution elasticity with higher rates in the power generation and energy intensive sectors.

Electrification of the economy: The increased use of electricity has been represented by higher substitution possibilities between electricity and other energy sources.

Decarbonisation of power generation: This is accomplished by switching to renewable and low carbon sources. The decarbonisation of power generation is achieved by deploying increasing renewable sources as well as considering also technologies such as carbon capture and sequestration in power generation only.

Four scenarios have been developed as an interpretation of the three specific narratives described in deliverable D2.2 “Co-design of macroeconomic and transition scenarios”. These scenarios are divided in two categories. The first category of scenarios shows the competitiveness effects in a world with a levelled playing field since there is a uniform carbon price all over the world, while the second category focus on the alternatives to level the playing field in a heterogeneous climate policy context with several carbon prices.

The first category is comprised by scenarios developed to represent the three narratives of Deliverable D2.2 assuming there is an international coordinated effort to implement a global climate policy. These scenarios have been simulated through a cost-efficient global carbon price in a context of global cooperation. This is equivalent to a global emission trading scheme (ETS) in which all countries in the world have a cap on emissions to comply with the agreed carbon budget, and at the same time each country can buy (sell) emission permits in the global carbon market if their current emissions are higher (lower) than their corresponding emission caps. The second category is comprised by a variant of one the previous scenarios developed to consider each country implements a domestic mitigation effort

which would lead to differentiated carbon prices in each region that would show more evident effects on competitiveness in regions with higher carbon prices. This choice allows analysing some of the policy options proposed to address the potential adverse effects on competitiveness described in section 1.3.

Current-NDC (NDC): Corresponding to the first narrative "*From NDC ambition to Paris compatibility*", this scenario represents the implementation of NDCs until 2030 with little or no increased ambition pledged during the round of negotiations in 2020 but requiring an increased effort after 2030 to comply with the long-term goal of 2°C by the end of the century. There is a global ETS and a uniform carbon price in all countries. Specifically, the scenario assumes an increase of energy efficiency in final uses, along with the deployment of renewable sources in power generation that is accelerated after 2030 to catch up with the required mitigation effort by 2050.

Enhanced-NDC (NDC+): Sharing the same carbon budget for the period 2010-2050 as the NDC scenario, it corresponds to the second narrative "*Increased 2030 ambition to Paris compatibility*" representing an acceleration of climate action in the short-term before 2030. This implies a smoother emission path allowing for higher emissions after 2035 compared to the NDC scenario. In this case, the adoption of energy efficiency measures, more efficient capital, renewable energy deployment, and electrification of the economy are intensified before 2030. As in the previous scenario, there is a global ETS and a uniform carbon price in all countries.

Enhanced-NDC (Domestic Effort) (NDC+ DE): Similar to the previous scenario but in this case the emission reductions are achieved by means of a domestic effort with differentiated regional and country carbon prices, with and ETS active only in European Union countries.

High-Decoupling 1.5C (HD-1.5C): With an emphasis on the long-term goal of 1.5° C by 2100 the carbon budget for this scenario is much lower than the previous NDC-based scenarios. This scenario corresponds to the fourth narrative of D2.2: "Behaviour-driven transformation to 1.5C", which is a combination of early action consisting in behavioural changes that allow for a reduced energy demand from the beginning along with low carbon technologies deployment. This choice has been made due to the limitations of the CGE model described in section 1.4, and also because the availability of carbon capture and sequestration technologies in ICES is restricted to the power generation sector while it does not account either for carbon dioxide removal from bioenergy nor land use and forestry activities. Therefore, the behaviour-driven transformation has been basically modelled in ICES in a simple and straightforward way as a reduced demand scenario (with lower growth) from the beginning that is also complemented with investments in more energy efficient capital in energy intensive sectors and power generation before 2030 at higher rates than the Enhanced NDC scenario. It is assumed a higher total factor productivity than in the previous scenarios representing the technological progress and innovation in all industries that allows for more efficient production processes. Along with these measures, the deployment of clean technologies provides the required energy supply to meet the future energy demand in a decarbonised economy after 2030. Also, in this case all mitigation efforts are coordinated with a global ETS and a uniform global carbon price.

One caveat of this exercise regards the availability of carbon dioxide removal alternatives in ICES which are restricted to carbon capture and sequestration in the power generation sector, because carbon capture and sequestration in other industries are not available in the CGE model. While this leads to produce a 1.5° scenario based on a reduced demand, an alternative would have been to assume the

removal of carbon as part of the storyline of the scenario which would have allowed for higher emissions. However, that exercise would not have provided additional insights to our analysis.

Figure 1 shows the evolution of global CO_2 emissions from energy use implemented in the ICES model for each one the narratives abovementioned. Note that even though both NDC-based scenarios share the same carbon budget for the period 2010-2050, the Enhanced NDC allows for a smoother transition albeit requiring an increased effort from the beginning. The global carbon budget of energy related CO_2 emissions for these scenarios is 1072 $GTCO_2$, while for the 1.5DG scenario it is 800 $GTCO_2$, which is around 75% of the NDC-based scenarios' carbon budget.

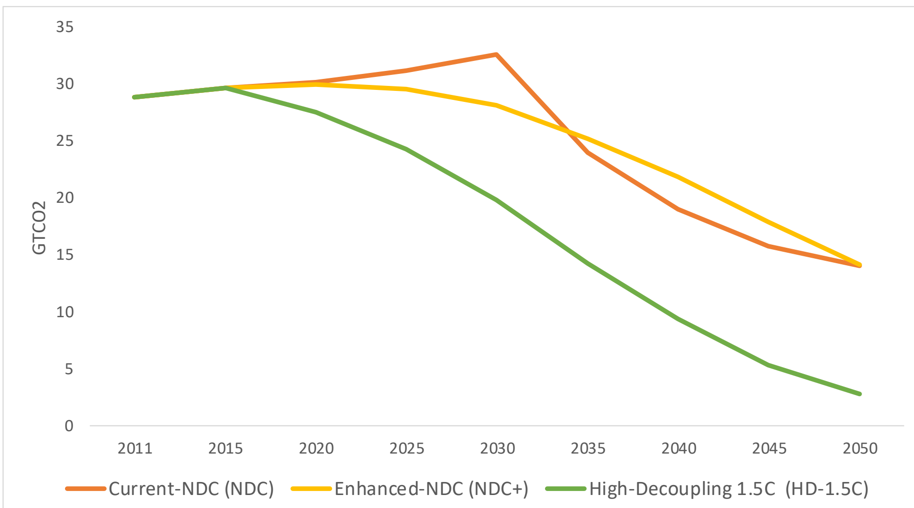

Figure 1: Global CO_2 emissions from energy use

The characterization of each scenario is summarised in Table 3 showing high level indicators for the periods 2011-2030, 2030-2050 as well as for the entire period 2011-2050. Both NDC-based scenarios simulated with a global ETS have a similar economic growth for the period 2011-2050 even though the NDC+ portrays a slightly higher economic growth in the second half of the period (2030-2050). This is due to the fact that despite an increased ambition starting before 2020, the costs of early action would be very similar to those of the NDC scenario. However, the main difference is noticeable in the period 2030-2050 where in the NDC scenario the economy must increase efforts to comply with the long-term goal of the Paris Agreement. This is reflected in lower GDP growth compared to the NDC+ scenario (176% vs 181%). By looking at the annual average growth rates (a.a.g.r.) of GDP, delaying action after 2030 would reduce the a.a.g.r. by 0.11 percentage points for the period 2030-2050. If the same Enhanced-NDC were achieved with a domestic effort (see NDC+ DE) the GDP growth would be lower (173%) than the other NDC-based scenarios. In addition, the a.a.g.r. for the period 2030-2050 would be much lower (2.47%) compared to the NDC+ scenario (2.62%). This scenario would be closer to the current climate policy context where despite setting a global long-term goal to keep temperature below 2 °C, the heterogeneous mitigation efforts show a suboptimal scenario. In fact, the GDP growth in the NDC+ (DE) scenario is closer to the HD-1.5C scenario (173% for both scenarios for the period 2011-2030). The HD-1.5C scenario shows lower economic growth since it follows a pathway based on reduced energy demand and increasing the ambition to be in the range of 1.5°C by the end of the century would

imply an a.a.g.r. of world GDP equal to 2.61% for the period 2011-2050 which is slightly lower than the NDC and NDC+ scenarios. At the country level, EU countries will grow between 1% and 1.8% on average each year with a slightly higher growth in the NDC+ scenario compared to the NDC. Developed regions would grow by less than 2% on a yearly basis, while developing regions could grow up to 5% per year (see Figure 40 in appendix A). The most noticeable difference emerges when comparing the a.a.g.r of the NDC+(DE) with a domestic mitigation effort against the NDC+ with the ETS. Almost all regions would grow more in the NDC+ scenario with the exception of USA, China, South Africa and former Soviet Union countries, given that they would have lower marginal abatement costs and would be selling emission permits in the global ETS scenario.

ICES provides information on CO_2 emissions from energy uses which by 2050 should be reduced by 51% compared to 2011 in all NDC-based scenarios with the higher effort in the period 2030-2050 for the NDC scenario (57% reduction). The emission reduction in the HD-1.5C scenario is about 90% compared to 2011, implying an almost decarbonized energy system with a reduction of 5.8% per year on average. The carbon intensity of GDP reduces more in the second part of the period (2030-2050) and by 2050 it shows a reduction of around 83% for the NDC based scenario and 97% for HD-1.5C.

Table 3: High level indicators from ICES simulated scenarios

	Growth rate			*Annual average growth rate*		
	2011-2030	***2030-2050***	***2011-2050***	***2011-2030***	***2030-2050***	***2011-2050***
GDP						
NDC	68%	64%	176%	2.76%	2.51%	2.63%
NDC+	68%	68%	181%	2.76%	2.62%	2.69%
NDC+ (DE)	67%	63%	173%	2.74%	2.47%	2.61%
HD-1.5C	68%	63%	173%	2.77%	2.46%	2.61%
CO2 emissions from energy use						
NDC	13%	-57%	-51%	0.65%	-4.11%	-1.82%
NDC+	-2%	-50%	-51%	0.65%	-4.11%	-1.82%
NDC+ (DE)	-2%	-50%	-51%	0.65%	-4.11%	-1.82%
HD-1.5C	-31%	-86%	-90%	-1.95%	-9.40%	-5.85%
Carbon intensity of GDP						
NDC	-33%	-74%	-82%	-2.06%	-6.46%	-4.34%
NDC+	-42%	-70%	-83%	-2.81%	-5.86%	-4.39%
NDC+ (DE)	-42%	-69%	-82%	-2.79%	-5.73%	-4.31%
HD-1.5C	-59%	-91%	-97%	-4.60%	-11.57%	-8.24%
Energy Intensity of GDP						
NDC	-17%	-8%	-24%	-0.99%	-0.44%	-0.71%
NDC+	-21%	-24%	-40%	-1.25%	-1.34%	-1.29%
NDC+ (DE)	-21%	0%	-21%	-1.24%	-0.01%	-0.61%
HD-1.5C	-33%	11%	-26%	-2.09%	0.53%	-0.75%
Carbon Intensity of Energy						
NDC	-19%	-71%	-77%	-1.08%	-6.04%	-3.66%
NDC+	-26%	-61%	-71%	-1.57%	-4.59%	-3.13%
NDC+ (DE)	-26%	-69%	-77%	-1.57%	-5.72%	-3.72%
HD-1.5C	-39%	-92%	-95%	-2.57%	-12.04%	-7.55%
Carbon tax 2011US$/TCO₂						
year	***2020***	***2025***	***2030***	***2035***	***2040***	***2050***
NDC	7	16	24	158	360	726
NDC+	7	23	48	106	208	528
NDC+ (DE)	[0 - 39]	[6 - 108]	[26 - 229]	[57 - 705]	[122 - 1245]	[299 - 2363]
HD-1.5C	21	68	181	403	737	2229

Interestingly, by looking at the energy intensity of GDP it is possible to understand the main difference between the NDCs-based scenarios and the HD-1.5C when there is a global ETS. All scenarios decrease the energy intensity of GDP in the period 2011-2030, but only the HD-1.5C scenario shows an increasing energy intensity of GDP after 2030 with an annual average of 0.53% for the period 2030-2050. This is a direct consequence of the assumptions made for this scenario, since the energy efficiency improvements are higher than the other scenarios from 2020 on showing a reduction of energy demand from 2011 to 2030 reflected in a 33% reduction of energy intensity of GDP. Then, in the subsequent period after 2030, there is an increasing energy intensity of GDP thanks to the deployment of clean and low carbon technologies. The most important aspect behind all scenarios is the carbon intensity of energy which is reduced by 77%, 71%, 77%, and 95% in the NDC, NDC+, NDC+(DE) and HD-1.5C scenarios respectively. While the major reduction of carbon intensity of energy is accomplished after 2030, the deployment of low carbon technologies in the 1.5°C scenario allows for a reduction of 95% of carbon intensity of energy while at the same time permits an increasing energy use.

In the case of a domestic effort in the NDC+(DE) scenario, there is a higher energy intensity for the period 2030-2050 compared to the NDC+ scenario due to the fact that most developing regions with marginal lower abatement costs are able to use more energy in order to achieve their domestic targets. Different is the case with a global ETS in which those countries should bear the higher burden of abatement reducing also their energy consumption as well, while most develop countries can buy carbon permits to offset their emissions and comply with their mitigation targets.

A final remark regards the carbon price for each scenario. This indicator should be regarded as a proxy for the effort required to comply with the economy-wide target of curbing emissions and its value should be considered in the context of the CGE model with all its caveats and limitations. In this case the carbon price reflects the signal needed to attain the target set for each scenario. In this context it is important to note that while the carbon price in the Enhanced-NDC (NDC+) scenario is twofold the value of the Current-NDC (NDC) scenario in 2030 (48 vs 24 US$/TCO2), but by 2035 and 2050 its value is 33% and 27% lower respectively showing the long-run benefits of early action (528 vs 726 US$/TCO2 in 2050). For the case of an early action but with a domestic mitigation effort (NDC+DE) the carbon prices are shown in intervals for each period. Noteworthy, the maximum price for each year corresponds to that of the EU ETS showing the higher marginal abatement costs in the EU28. Finally, the HD-1.5C scenario contemplates higher prices echoing the higher ambition of reducing global emissions. These higher prices indicate that in the CGE framework there are some sectors that are still using carbon-based energy facing specific rigidities in a decarbonization transition.

5 Industrial competitiveness and Industrial policies in a climate policy context

The effects on competitiveness when a climate policy is implemented depend on the combination of the main concurrent drivers which are related to: i) the increase in production costs (mainly due to higher abatement costs or higher energy costs), ii) the energy intensity of the industry, and iii) the type of energy used in the production process. Basically, a mitigation policy will increase production costs by putting a price on emissions in such a way to discourage the use of pollutant energy sources and encourage innovation in production processes either to abate emissions or to switch to low carbon energy sources. A direct example of this is a carbon price or tax that increases the costs of fossil fuels.

This is also directly related to the energy intensity of the industry. The higher the energy use, the higher could be the increase in production costs depending on the type of energy source used. On one side, if an industry relies on high carbon fuels then it will be negatively affected until it could switch to clean or renewable energy sources. On the other side, if the industry's production process is based on renewable sources then it will have a relative advantage over industries using fossil fuels.

This section will analyse the effects on competitiveness from two different types of policy. The first type focuses on some of the policy options to address competitiveness concerns summarised in section 1.3, specifically Border Carbon Adjustments (BCA) and Output Based Rebates (OBR) which will be also compared to a scenario with a uniform carbon price where there would be no need for additional policies to address competitive concerns. The second type of policy analysed is a set of industrial policies identified in communications and strategies published by the European Commission in the last years. Some of them also address industrial strategies within a context of decarbonisation such as the deployment of renewable sources to support industrial processes while other include supporting sectoral agreements to increase the demand of industries such as Iron & Steel, or international agreements that could support also climate and decarbonisation policies.

5.1 Effects of implementing policies to address competitiveness

While putting a price on carbon emissions seeks to spur innovations and to foster the use of clean energy sources, the initial effects on energy intensive industries could bring about competitiveness loss concerns. To address this concerns many alternative policies have been proposed as summarised in section 1.3, which try to level the carbon costs of these industries either by rebating part of the incurred carbon costs to those industries or by extending the carbon costs to foreign industries by means of border carbon adjustments. This section will focus on two policy options to address competitiveness considering Border Trade Adjustments (BCA) and Output Based Rebates (OBR) with the following variants of the NDC+ (DE) scenario:

NDC+ (DE) EU BCA: Same as NDC+ (DE) scenario with the EU imposing a Border Carbon Adjustment in the form of an import tariff based on the carbon content of all imported commodities.

NDC+ (DE) EU OBR: Same as NDC+ (DE) scenario with the EU implementing an Output Based Rebate (OBR) of the carbon cost for EITE industries only. The carbon cost rebate is implemented as an output subsidy equivalent to the carbon price payed by each EITE industry.

This allows considering a set of four scenarios to analyse the effects on competitiveness. The NDC+ (DE) scenario is used as reference where there are differentiated domestic mitigation actions and carbon prices which would produce more evident effects on competitiveness. This reference is compared to the two scenarios implementing measures to level the playing field for EU industries (BCA and OBR) and also is compared to the NDC+ scenario where there is a global carbon price meaning that there would not be a need to level the carbon costs in EU industries, also given that industries have the possibility to buy emission permits abroad.

5.1.1 Effects at the industry level

To understand the effects on competitiveness, this section presents a first example for the Iron & Steel industry and a second example for the chemicals industry both in two different countries. Figure 2 shows the four selected scenarios focusing on: a) Changes in production compared to the NDC+ (DE) scenario, b) the evolution relative competitiveness, and c) energy consumption by type of energy for the Iron & Steel industry and for two countries with a similar output level in 2011: France and Italy.

It is important to frame the following results in the right context, since the ICES model is based on data coming from national accounts, input/output, and social accounting matrices which have activities aggregated at the level of macro sectors. Therefore, it does not model the complex details of a particular industry but relies on the representation of each macro-industry provided by the national accounts data. However, the following results provide some insights about the industrial implications of decarbonisation scenarios along with some policy options to address competitiveness which should be complemented with more in-depth studies for each sector (see for example Bataille et al., 2018b, and Droege et al., 2010). This analysis could be also complemented by using a CGE model extended with a more detailed modelling of the Iron & Steel industry which has been used for circular economy and resource efficiency analysis (Winning et al., 2017).

Panel a) of Figure 2 shows the changes in output with respect to the NDC+ (DE) scenario which is plotted as a horizontal red line with the square marker. Both policy options to address competitiveness would increase output in both countries. BTAs are effective in the short-term and have a similar effect on output as OBR only during the first five years. Afterwards, OBR would be the most effective measure. The decline of the positive effect of BTAs (implemented as an import tariff based on the carbon intensity of imports) in a decarbonisation scenario is as expected since by 2050 the world CO2 intensity of GDP would have decreased by more than 82% (see Table 3) and therefore the carbon intensity of imported commodities should have also decreased. The OBR also shows a similar trend after 2035 for the same reasons given that the rebate or carbon costs should also decline in a less carbon intensive world. However, the effect is higher than a BTA because the carbon rebate is implemented as an output subsidy and this means that the industry could use the value of the rebate to invest in new and more efficient capital which will increase output in the long term more than in the BTA scenario. Notwithstanding the positive effect of both measures on output, the NDC+ scenario with a global ETS shows a higher output since EU industries can produce more and buy permits abroad to offset emissions. This scenario would represent an optimal solution from the economic viewpoint by shifting the mitigation effort to those regions with lower marginal abatement costs.

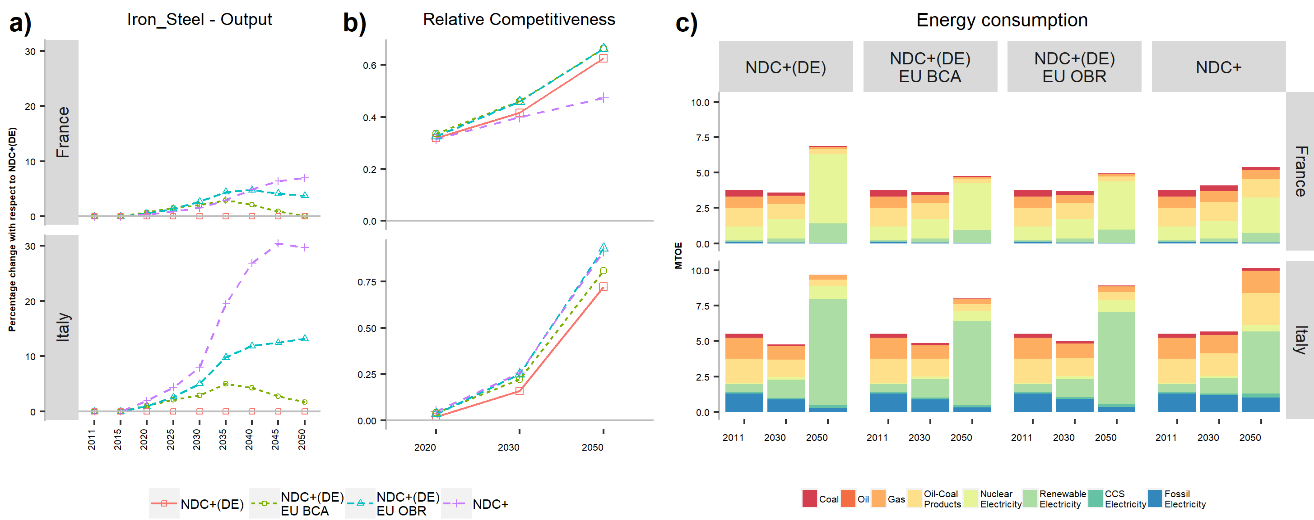

Figure 2: Effects of BCA and OBR and a global ETS on production and competitiveness in the Iron & Steel industry for France and Italy

The competitiveness effects are shown on panel b) of Figure 2 with the relative competitiveness (RC) indicator introduced in section 0. Both measures (BCA and OBR) improve in a similar way the relative competitiveness of the industry in France, while in Italy the OBR shows a more positive effect than BCA when compared to the NDC+ (DE) scenario (red line). Interestingly, competitiveness is differently affected in the scenario with the global ETS (NDC+) since there is a lower RC for France, while in Italy it is close to the OBR scenario showing an improvement in competitiveness compared to the NDC+ (DE) scenario. The fact that in the NDC+ scenario the Iron & Steel industry in France shows a lower RC means that in relative terms is less competitive than the rest of the industries. Moreover, in the same scenario not only output is higher than in the other 3 scenarios from 2040 on, but also net exports are also higher. What explains a lower RC for Iron & Steel in France is the fact that the rest of the industries are exporting even more in relative terms. However, it is worth nothing that the RC index is increasing in all scenarios.

The main difference in the Iron & Steel industry between France and Italy is highlighted in panel c) of Figure 2. In 2011 the Iron & Steel industry in France uses more nuclear electricity, while in Italy relies more on fossil and renewable electricity. This difference remains in time since in 2050 France continues to rely more on nuclear electricity even though the share of renewable electricity grows more than fivefold. Italy shows the opposite, relying more on renewable electricity (and also importing a small share of nuclear electricity). This would also explain why the relative competitiveness has a steeper improvement in Italy since the industry uses more renewable electricity when the carbon price is higher, while France has already a low carbon source of energy and even though the consumption of renewable energy increase, also does the use of nuclear electricity.

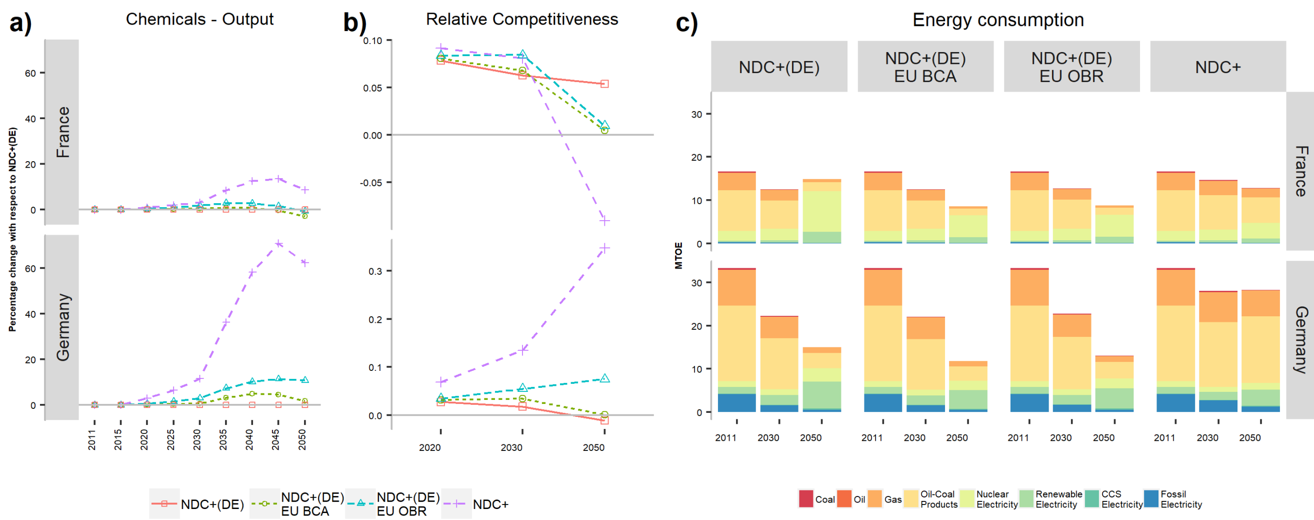

Figure 3: Effects of BCA and OBR on production and competitiveness in the Chemicals industry for France and Germany

For the second example, Figure 3 shows the same information for the chemicals industry for France and Germany which are the countries with the highest production of the chemicals industry within the EU with slightly different energy mix consumption, since Germany uses more electricity generated with fossil fuels. The effects on output are like the Iron & Steel industry since both BTA and OBR increase output, although there is a slightly lower output in France in 2050 when BTAs are implemented as shown in panel a) of Figure 3. Regarding relative competitiveness, while the chemicals industry has a positive RC value until 2030, depending on the scenario and on the country this indicator would show a competitive disadvantage in 2050 (see panel b). An important difference with the previous example is that the Chemicals industry uses more fossil fuels and emits more CO_2 emissions than Iron & Steel despite being less carbon intensive in terms of output (see also Figure 10). From the different types of energy used presented in panel c) of Figure 3, fossil fuels represent a major share with low carbon electricity providing less than 16% and 9% of energy to chemicals production in France and Germany, respectively. This shows the potential difficulties the industry could face to shift to low carbon energy sources. In fact, in all scenarios presented in Figure 3 the Chemicals is industry would still be using a significant share of fossil fuels in 2050.

This rigidity in switching to renewable sources would explain the reduction in competitiveness in all scenarios. It is important to acknowledge that the rigidity of the chemicals industry is inherent to the CGE model given that it cannot represent all the details of the industry. A detailed discussion of the alternatives for the chemicals industry in decarbonisation pathways includes the use of biomass and carbon capture and utilization or storage as part of the elements needed for decarbonising the industry which are currently not present in the CGE model analysis (see Bataille et al., 2018b; Griffin et al., 2017; Griffin et al., 2018 for literature on emission reduction on the Chemicals sector).

5.1.2 Effects for the EU EITE industries

The effects of both BCA, OBR and a global ETS for EITE industries aggregated at the EU28 level compared to the NDC+(DE) scenario are shown in Figure 4. For all EITE industries the OBR shows better results than BCA. However, OBR are more effective in more carbon intensive and high emitting industries such as Non-Metallic Minerals, Iron & Steel, and Chemicals, while less carbon intensive industries have a small or null effect. Moreover, BCA have a negative impact in less carbon industries since the carbon-based tariffs increase the costs of imported inputs. The enhanced NDC (NDC+) scenario with the global ETS shows always better result for all EITE industries because they can produce more and at the same time buy emissions permits abroad in order to offset emissions.

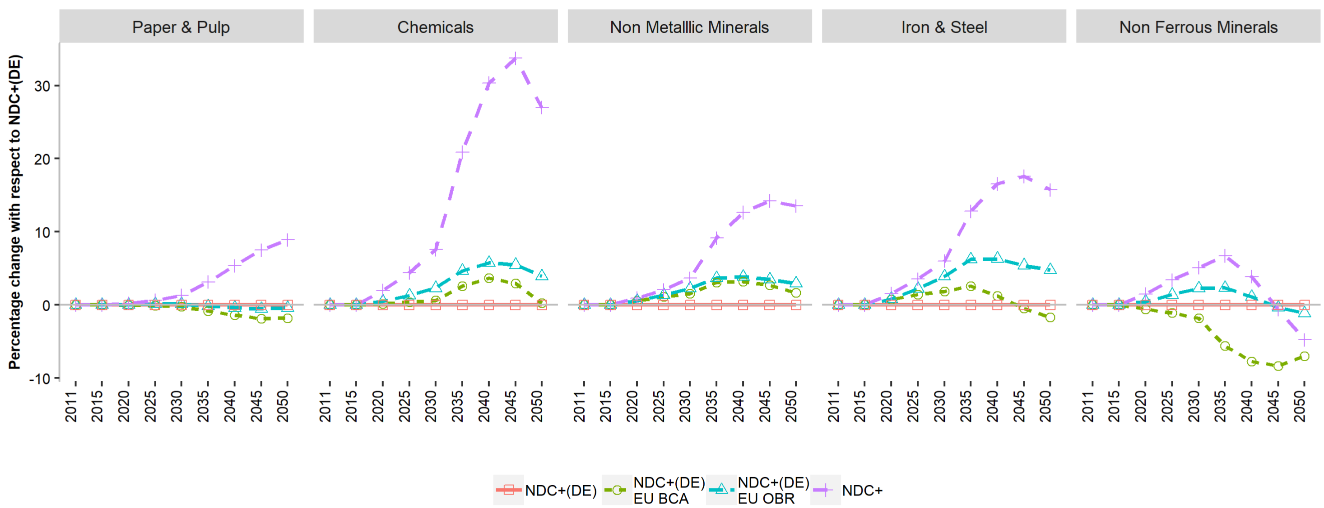

Figure 4: EU28: Effects of BCA and OBR on Output of EITE industries

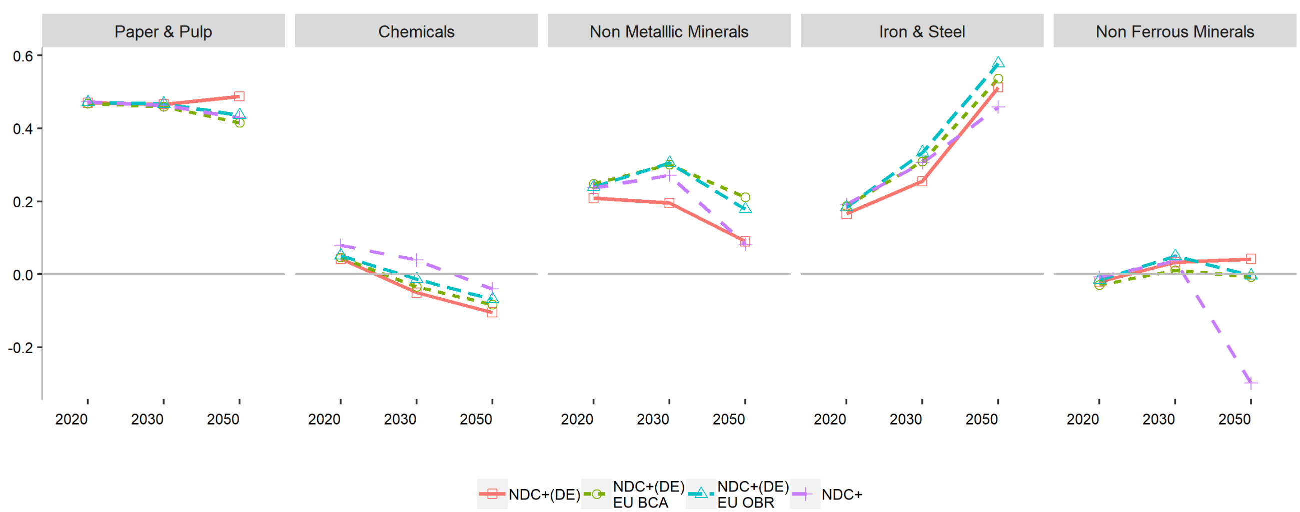

Figure 5: EU28: Effects of BCA and OBR on Relative competitiveness of EITE industries

Looking at the relative competitiveness of EITE industries shown in Figure 5, a similar conclusion emerges since OBR present better results than BCA and that high carbon intensive and high emitting industries are favoured by the OBR policy. This is confirmed when looking at the lower RC indicator in

2050 for Paper & Pulp and Non-Ferrous Minerals. Interestingly in the global ETS scenario (NDC+) only the Chemicals industry shows a higher RC indicator and a much higher production (see Figure 4) implying that it would be the industry which would buy more emission permits given the difficulties to decarbonise its production process.

5.2 Industrial policies in a climate policy context

The European Union has released a series of communications, strategies and plans for specific sectors promoting industrial policies (EC, 2017a, 2017b; Szczepański and Dobreva, 2018). Among EITE industries, the Steel plan released in 2013 (EU COM, 2013) and the vision for Non-ferrous metals manufacturing (Dessart and Bontoux, 2017) provide specific policies that can be implemented in ICES as additional simulation scenarios. For this purpose, this section will first focus on the Iron and Steel sector by comparing three decarbonisation scenarios and then the following subsections will use the Enhanced NDCs scenario as a point of comparison to include a set of industrial policies extracted from the literature mentioned above. Specifically, there are four elements which can be included in the simulated scenarios with ICES.

The first one regards the energy, climate and resource efficiency policies to boost competitiveness (EU COM, 2013; Dessart and Bontoux, 2017), to promote affordable energy prices, and to reduce supply energy costs. This is directly related to climate policy and can be modelled in ICES as an increase in the deployment of renewable power which leads also to a decrease of renewable electricity prices.

The second point is related to International trade by pursuing a trade liberalisation agenda through the negotiation of Free Trade Agreements (FTAs) to ensure access to third country markets and raw materials as well (EU COM, 2013, and Dessart and Bontoux, 2017). This can be easily implemented in ICES by taking up the discussion about removing import tariffs within a group or countries.

The third element regards international cooperation and climate policy. As part of the Steel plan, the medium to long term goal was to pursue negotiations towards concluding a binding international agreement on climate change. With the Paris Agreement this has been partially accomplished and even though the pledges might not be ambitious enough nor the targets binding, it actually sets a new policy context in which almost all countries in the world have acknowledged the need to address climate change. While this has already been included in the decarbonisation scenarios it is also possible to simulate cooperation among countries by means of coalitions built around a climate policy objective, following the idea of climate clubs (Grubb et al, 2015; Nordhaus, 2015). This can be represented in ICES by simulating a scenario with a coalition of countries implementing not only a climate policy but also a series of measures to strengthen and enforce the coalition agreement such as increased technology diffusion and reductions of capital costs within the climate club plus imposing border carbon adjustments or import tariffs on EITE imports.

A final point considers increasing demand for steel as mentioned in the Steel action plan (EU COM, 2013) which should be done by promoting growth in key steel-using sectors such as construction, automotive, engineering, and electrical and electronic equipment sectors. This is indirectly related with technology diffusion in ICES, since the Vehicles and Machinery & Equipment sectors are directly related

to the technology spillovers embodied in international trade. Therefore, increasing their trade and output can increase demand for steel and raise energy and capital productivity in sectors and industries importing these commodities. One way of simulating this policy is by liberalising trade of those commodities as well as increasing the spillovers coefficient in the ICES model.

5.2.1 An example of sectoral implications for the Iron & Steel sector

The implications on trade and competitiveness in decarbonisation scenarios are direct consequences of the assumptions used to build each scenario. As explained in section 4. there are three main pillars on which each scenario has different assumptions, namely: i) Energy efficiency, ii) Electrification of the economy, and iii) Decarbonisation of power generation. To better understand the effects of these choices Figure 6 shows an example of the evolution of a) production, b) relative competitiveness and c) energy consumption by type of energy for the Iron & Steel industry in the three decarbonisation scenarios for two countries that had a similar output level in 2011: France and Italy.

Panel *a)* shows the industry output for the period 2011-2050 with a slightly higher production in the Enhanced NDCs scenario (green dashed line) than the NDCs scenario (red line), while the 1.5DG scenario represents a more stringent scenario based on a reduced demand storyline showing lower output (blue dashed line) than the NDCs-based scenarios. When the NDC+(DE) scenario is attained with domestic efforts and at higher carbon prices, the output is lower than the NDC+, given that the industry is not able to buy emission permits abroad. Whereas production trends are similar for both countries, there are different competitiveness effects as shown in panel *b)* with the relative competitiveness indicator. Whilst France would be better off in the 1.5 DG scenario, with a lower competitiveness in the NDCs scenario and much lower RC in the Enhanced NDCs scenario, Italy shows the opposite behaviour. Each behaviour can be explained by looking at the energy consumption of the Iron & Steel industry in each country represented in panel *c)* of Figure 6.

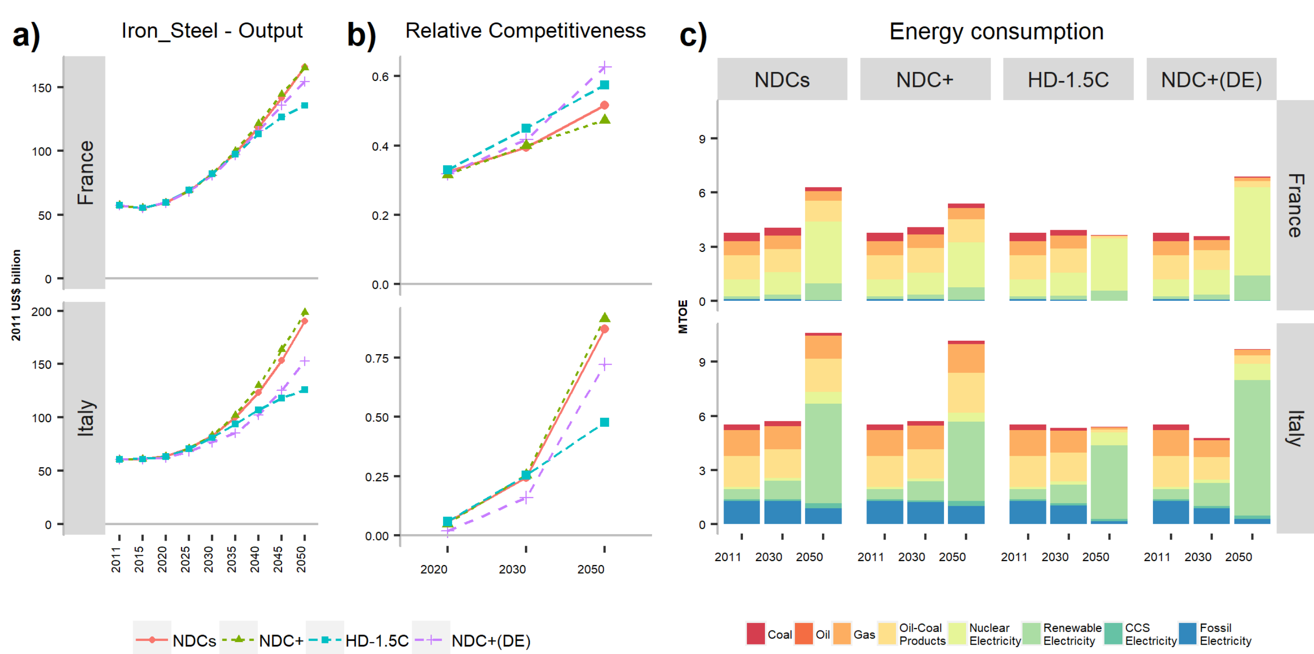

Figure 6: Production and competitiveness in the Iron & Steel industry for France and Italy

There are two main differences between these industries. The first is that the French industry is more energy efficient than the Italian one since it uses less energy for a similar quantity of output in 2011. The second difference is that the Iron & Steel industry in France uses more nuclear electricity, while in Italy relies more on fossil and renewable electricity (as mentioned in section 5.1.1). The fact that both countries still use a large share of fossil fuels as energy in 2011 explains why they can still produce at the levels of the NDCs-based scenarios in the following years. Output in France is very similar for the NDCs and Enhanced NDCs scenarios, while in Italy the Enhanced NDCs reports higher production for the industry. The higher production levels in the NDCs-based scenario in both countries are because by 2050 they are still using fossil fuels as energy. In fact, the industry uses not only more renewable electricity in 2030 which by 2050 would constitute more than half of energy consumption, but also uses more fossil fuels as well.

Moreover, in an almost fully decarbonised scenario such as 1.5DG where energy use is much lower, it is the deployment of clean energies what influences the behaviour of the industry's output. In the case of France, the availability of nuclear electricity allows to use more of it instead of fossil fuels since it is already a low carbon energy source, although renewable electricity is also ramping up. Conversely, the Italian industry must deploy more renewable electricity to substitute for fossil-based electricity and for other fossil fuels. This implies a higher cost for the transition since there is a clean energy sector that must be developed. Finally, the energy use in the NDC+(DE) scenario shows a much higher use of low carbon electricity both in France and Italy, which is the result of a higher carbon price that spurs the deployment of renewable electricity (besides nuclear in France). This scenario shows also a lower but still positive relative competitiveness in Italy, while in France it is higher thanks in part to the initial advantage of using nuclear as a low carbon electricity source.

5.2.2 Increasing renewable technology deployment

Technology diffusion and deployment is one of the elements that could be used in a green development strategy. To assess the implications of this kind of policies, this section will present a variant of the Enhanced NDCs scenario in which renewable technologies are deployed at a faster rate (Enhanced NDCs + RES).[4] This has been modelled by means of higher rate of exogenous technological change (or total factor productivity - TFP) on the power generated from renewable sources as shown in Figure 7.

[4] We selected this technology based on the technologies identified in table 1-1 of D3.3 which in the ICES model are represented by the electricity generated with renewable sources.

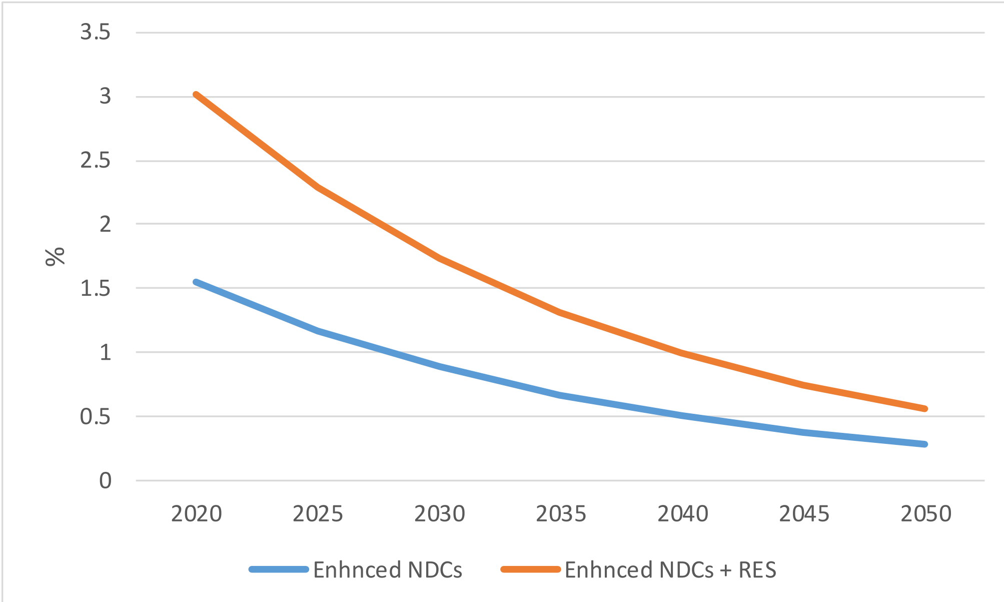

Figure 7: Annual average growth rate of TFP in renewable power generation

Figure 8 shows the effects on the Iron & Steel sector comparing both scenarios in France and Italy. Output is slightly lower in the new scenario (Enhanced NDCs + RES) in France since, as said in the previous section, the French Iron & Steel industry relies more on nuclear electricity and the benefits of an increased deployment of renewable technologies are observed in 2050 when there is a much higher generation and consumption of renewable energy. This suggests that it takes time for renewable electricity to gain a major share of energy consumption, because during the first years there are energy efficiency measures put in place combined with relatively low mitigation targets until 2030. This can be better illustrated with the Italian Iron & Steel industry that can produce more from the beginning of the policy implementation and it is able to substitute more fossil fuel-based energy with renewable sources from 2030 on in the "Enhanced NDCs + RES" scenario as shown at the bottom of panel *c)* in Figure 8. A final remark for this new scenario is that the relative competitiveness indicator improves in Italy. This outcome together with the fact that the industry output is higher show the benefits of early deployment of more renewable energy sources but to the disadvantage of nuclear electricity and Iron & Steel output in France.

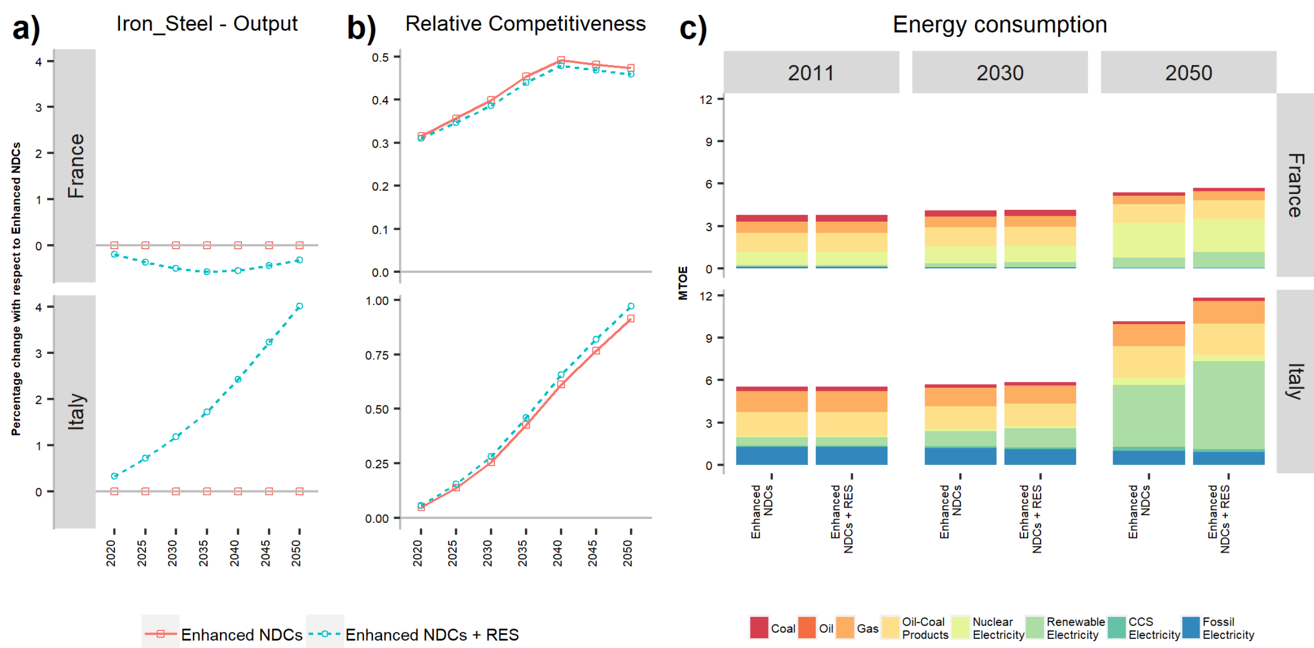

Figure 8: Effects of an increased renewable energy deployment in the Iron & Steel sector

5.2.3 International cooperation in the form of climate clubs

To explore the effects that international cooperation could play through trade-related technology diffusion this section presents a scenario based on a climate club formation considering the specific aspects of international cooperation among club members. Building on Deliverable D3.3 of the Green Win project[5] the Climate Club would be formed by countries with a strong commitment to mitigate emissions and/or with a high potential to do it, namely: the EU28, Japan, China, India, and Brazil. Considering this coalition, we formulated the following scenarios to provide additional examples of international cooperation.

CClub1: There is a more active technology transfer between members. At the same time there is a trade liberalisation (FTA) for Vehicles and Machinery & Equipment imports within the coalition and a reduction in capital costs for renewable power generation. The technology transfer has been simulated in ICES firstly by increasing the embodied technology spillovers coefficient among the coalition members and secondly by removing the import tariffs of Vehicles and Machinery & Equipment trade within the coalition (According to the GTAP database these tariffs within the coalition would be in the

[5] Deliverable D3.3: "Mitigation and adaptation pathways and their macroeconomic impact" available at https://green-win-cloud.org/index.php/s/GCnTZSRD9WDUSlG

range of 1% to 13%). The last element of this scenario is an initial reduction of capital costs of 1% in the renewable electricity generation effective in 2020.

CClub2: Similar to *CClub1* but with trade liberalisation extended to the Iron & Steel industry within the coalition where tariffs would be between 1% to 15%.

CClub3: Similar to *CClub1* but with trade liberalisation extended to all EITE industries within the coalition. The tariffs within the club would be between 2% and 13% for Paper & Pulp, 1% to 9% for Chemicals, 1% to 12% for Non-Metallic minerals, and 1% to 9% for Non-Ferrous Minerals.

CClub4: Similar to *CClub1* but with an initial reduction of capital costs of 5% in the renewable electricity generation effective in 2020.

CClub5: Similar to *CClub1* but raising Iron & Steel imports tariffs to 15% for all countries outside the club.

Results for the five club scenarios for Iron & Steel production for all regions in the world, in 2030 and 2050 are shown in panel *a)* of Figure 9. The package of policies implemented in the CClub1 scenario fosters the production of renewable energy and at the same time allow for an increased efficiency of capital and energy used in production processes due to the trade liberalisation of commodities embodying technology spillovers (Vehicles and Machinery & Equipment). Consequently, Iron and Steel output is slightly higher in all club members but Germany and Japan with small effects in the rest of the world (see square red marker in Figure 9). With the free trade agreement only for the Iron & Steel industry within the climate club (CClub2 – X marker) output could grow more than 2% compared to the Enhanced NDCs scenario by 2050. When the FTA is extended to all EITE industries (CClub3 – triangle marker) then Iron & Steel industry in all club members produces more but not as much as in the CClub2 scenario, with the exception of Brazil that actually ends up reducing production in almost all club scenarios. Reducing capital costs in renewable electricity generation by 5% instead of 1% (CClub 4 – cross marker) show similar results as the CClub1 scenario with a slightly increased Iron & Steel output only in Italy compared to the CClub1 scenario. When coalition members impose a tariff on Iron & Steel imports from countries outside the coalition equal to 15% (CClub5 – round marker), all club members would be better off increasing production between 0.87% (China) and more than 6% (EU countries) with the exception of Brazil that shows a small negative reduction of output in 2050. In contrast, countries outside the climate club could reduce their output by more than 10% (SASIA).

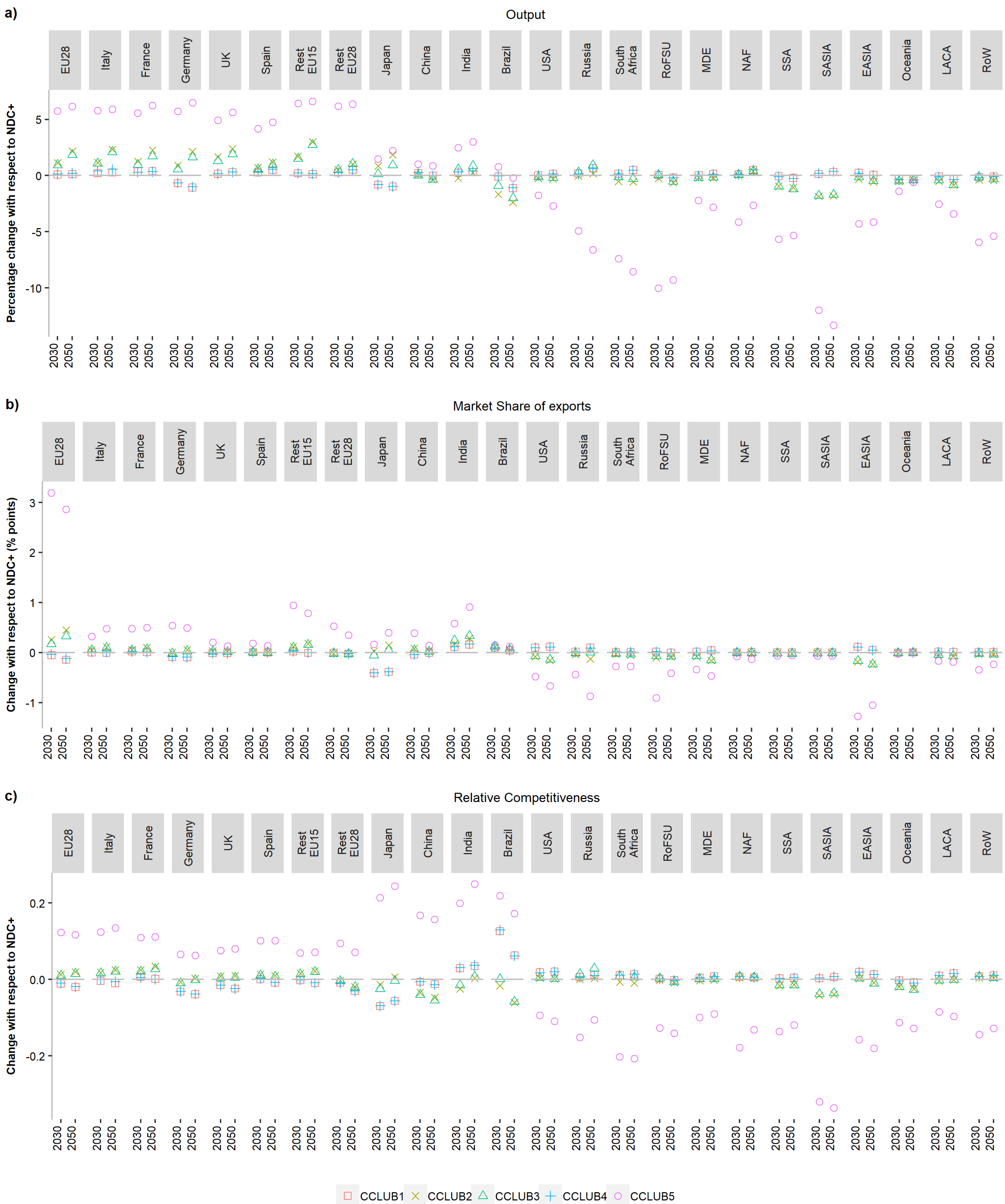

Figure 9: Effects of a Climate Club coalition in the Iron & Steel sector

The effects of creating a climate club on trade and competitiveness are displayed in panels *b)* and *c)* of Figure 9. Compared to the Enhanced NDCs scenario, and the countries from the climate club that increase the most their export share in 2030 are India and Brazil in the CClub1 and CClub4 scenarios when simulating a reduction in capital costs for renewable power generation. Conversely Japan shows a deterioration of their market share. The rest of the world has also small effects with the exception of United States and EASIA which increase their market share (see panel *b)* of Figure 9). The scenarios with trade liberalisations of the Iron & Steel (CClub2) and all EITE industries (CClub3) increase slightly the market share of exports in all club members. When the climate club imposes a tariff on Iron & Steel imports the market share of EU28 increases around 3 percentage points in total with the rest of the coalition members being much better off than in the other club scenarios. In this last case, countries outside the coalition that are worse off are USA, Russia, and EASIA.

In terms of relative competitiveness (see panel *c)* of Figure 9), in the CClub1 and CClub4 scenarios only India and Brazil improve their competitiveness which could signal that technology diffusion and lowering capital costs could constitute a good reason to join and stay in the coalition for both countries, even though the rest of the coalition is slightly worse off. However, the changes in the RC indicator in the rest of the world are negligible. With the trade liberalisation within the climate club of Iron & Steel (CClub2) and all EITE industries (CClub3) most western EU countries improve their competitiveness except for Germany, while in the rest of the club Japan, China, India, and Brazil would also see their relative competitiveness slightly deteriorated.

With a tariff on Iron & Steel imports from outside of the club, the relative competitiveness of the club members improves while that of the countries of the rest of the world is deteriorated. Finally, comparing across scenarios, only Japan sees the market share and relative competitiveness deteriorated in the CClub1 to CClub4 scenarios. This would indicate that an additional set of policies would be needed in order to keep the country within the coalition if the club does not implement FTAs on EITE industries.

6 Decarbonisation implications at the industry level for the EU

This section presents an overview of decarbonisation scenarios with a global ETS and a uniform carbon price to show results within a levelled playing field or, in other words, a climate policy context where there is no need to implement additional policies to level the costs of carbon. In this way it is easier to understand the potential advantages and disadvantages of industries within a climate policy. This section presents results for seven industries at the EU28 level. Five of them are the so-called Energy Intensive Trade Exposed (EITE) industries while the other two represent the industries that could support a low carbon development (Vehicles and Machinery & Equipment). The analysis is introduced by first focusing on effects on carbon intensity, carbon emissions, output, competitiveness, and labour costs; and afterwards presenting detailed results on trade and competitiveness for each selected sector as well as at the country level within each sector. A detailed analysis of trends for all indicators presented in section 2 for selected industries in Europe is available on Appendix A.

6.1 Overview of decarbonization scenarios

The evolution of carbon intensity by sector for the EU28 is shown in panel *a)* of Figure 10 from 2020 to 2050. The most carbon intensive industries, also known as the group EITE industries, are Non-Metallic Minerals, Iron & Steel followed by Chemicals, Non-Ferrous Metals and Paper & Pulp. Following are the Vehicles and Machinery & Equipment industries that have a much lower carbon intensity and that constitute an important share of industrial output, as shown on Figure 11. However, the most emitting industries are Chemicals, Non-Ferrous Metals and Iron & Steel (see panel *b)* of Figure 10). This indicates that an industry such as Chemicals with a relative low carbon intensity emits as much as the higher carbon intensity industry (Non-Metallic Minerals) and that the mitigation actions in this industry will be as much as important as industries with a higher carbon intensity.

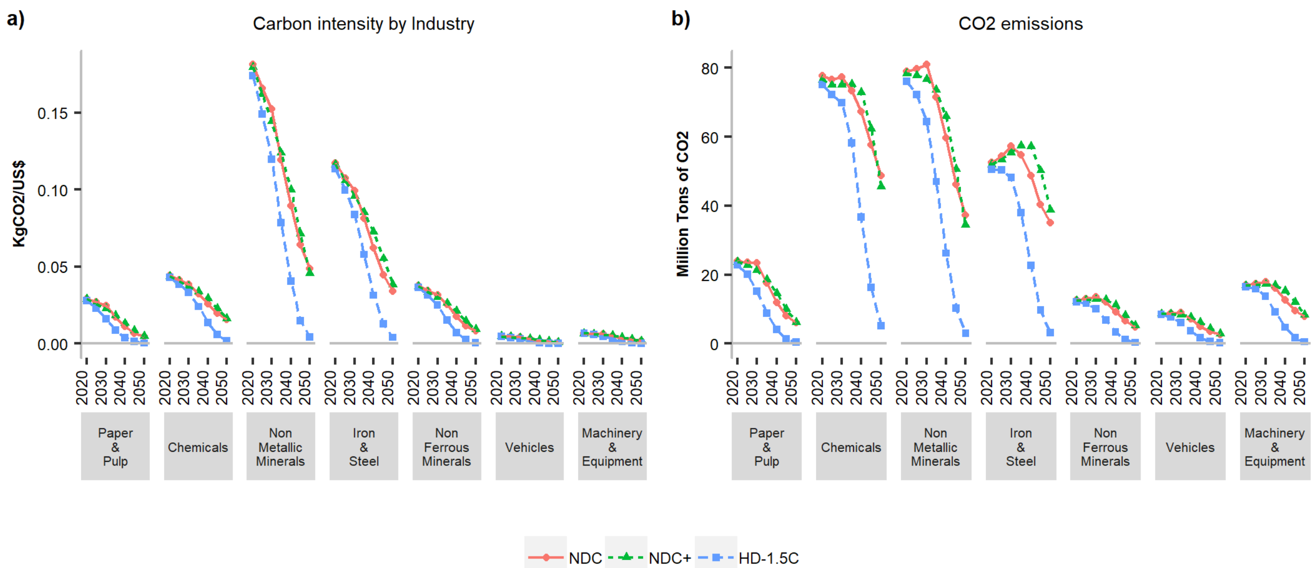

Figure 10: EU28: Carbon intensity and CO2 emissions by industry

Industrial production in the seven selected sectors does not differ very much across the three scenarios for 2030 as shown in panel *a)* of Figure 11. The increased ambition of the Enhanced NDCs scenario (NDCs+) does not affect much industrial output and remains at similar levels even in 2050, with the exception of Chemicals which is the sector experiencing the highest contraction of output in 2050 in opposition to less carbon intensive sectors such as Vehicles and Machinery & Equipment that increase output compared to the NDCs scenario where the mitigation effort is concentrated after 2030. Panel *b)* of Figure 11 highlights the long-run advantages of early action for these two industries and for the more carbon intensive sectors such as Non-Metallic Minerals and Iron & Steel that, differently from Chemicals, do not reduce as much their output. A similar conclusion could be drawn when looking at the 1.5DG scenario where, despite having a carbon budget that is 25% lower, the industrial outputs for some industries remain close to those of the NDCs-based scenarios (see all EITE industries except for Iron & Steel plus the less carbon intensive industries). Again, this is related to the storyline that depicts a lower consumption and economic growth by 2050 to attain the 1.5°C by the end of the century.

The evolution of the Chemicals industry reveals the rigidity in abating emissions that is more evident in 2050 when output declines even in the NDC+ scenario despite having a lower carbon price than the NDC scenario. This indicates that up to 2030 the Chemicals industry can produce a similar volume of

output in the NDC and NDC+ scenarios thanks to the fact that it can also buy permits from abroad (see section 5.1.2) and produce even more in the HD-1.5C thanks to the assumption that there should be more technical progress in all industries to achieve a more ambitious long-term goal of 1.5°C (see panel *b)* of Figure 11). However, since in 2050 world emissions must be abated by 90% with respect to 2011 (see Table 3) all industries must contribute to this target including Chemicals which is not able to buy all the permits it needs to maintain production and must invest in more low carbon energy instead of fossil fuels as shown in section 5.1.1 and Figure 3 with the NDC+(DE) scenario.

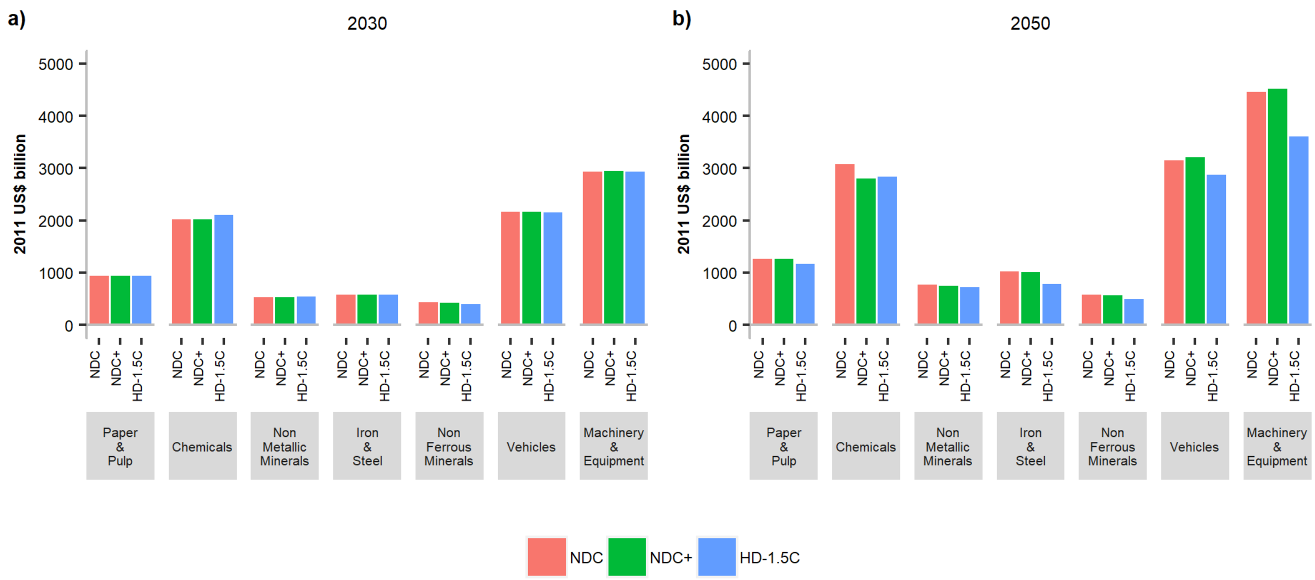

Figure 11: EU28: Output by industry for 2030 and 2050

To summarise the effects on trade for this overview, the Relative Competitiveness (RC) has been chosen an indicator (see Figure 12). Recalling from section 2, if RC is positive it means there is a revealed comparative advantage in that industry. Since the indicator considers export and import flows compared to the rest of the economy and to the rest of the world it also provides a measure of competitiveness (or relative competitiveness as defined by Vollrath, 1991). This indicator shows that at the EU28 level, five out of the seven selected industries would have a revealed comparative advantage from 2020 on (Paper & Pulp, Chemicals, Non-Metallic Minerals, Iron & Steel, and Vehicles). Even though Non-Ferrous Minerals and Machinery & Equipment do not show a comparative advantage at the EU28 level there are some countries from Western Europe such as Italy, France, Germany, and Spain that would show a revealed comparative advantage (see also Figure 35 and Figure 39 on Appendix A).

While the mitigation effort clearly shows a reduction in carbon intensity and emissions in all industries, the changes in trade and competitiveness indicators do not imply that an industry will always be worse off in a more ambitious scenario. For instance, comparing the NDC (red line) and Enhanced NDC (NDC+, green line) scenarios, the EITE industries show a decline in relative competitiveness when the mitigation effort is increased, but the opposite occurs when looking at the Vehicles and Machinery & Equipment industries, given that their carbon intensity is much lower. This would confirm the concerns about the loss of competitiveness in EITE industries. However, by looking at a scenario in which there is even a

higher mitigation effort such as the 1.5DG scenario simulated by means of an initial reduced energy demand along with increased efforts for technology developments and low carbon technology deployment, there are sectors such as Chemicals, and Non-metallic Minerals that could have an increased revealed comparative advantage, at least in the first decades. This could suggest that an enabling condition for such industries would be investing in first energy efficiency until low carbon technologies become available at affordable costs. The divergence among scenarios with a higher RC indicator for the HD-1.5C scenario is explained because the initial rigidity of the Chemicals industry is greatly reduced by a higher technical progress and innovation, along with the deployment of renewable energy sources that allows the industry to be more efficient from the beginning and shift to a low carbon energy source. This plus the fact that it can buy permits from abroad affects positively the relative competitiveness of the industry. On the contrary, in the scenarios where there is an increased mitigation effort (NDC and NDC+) but without the technical progress and innovation of the HD-1.5C scenario, the relative competitiveness is much lower.

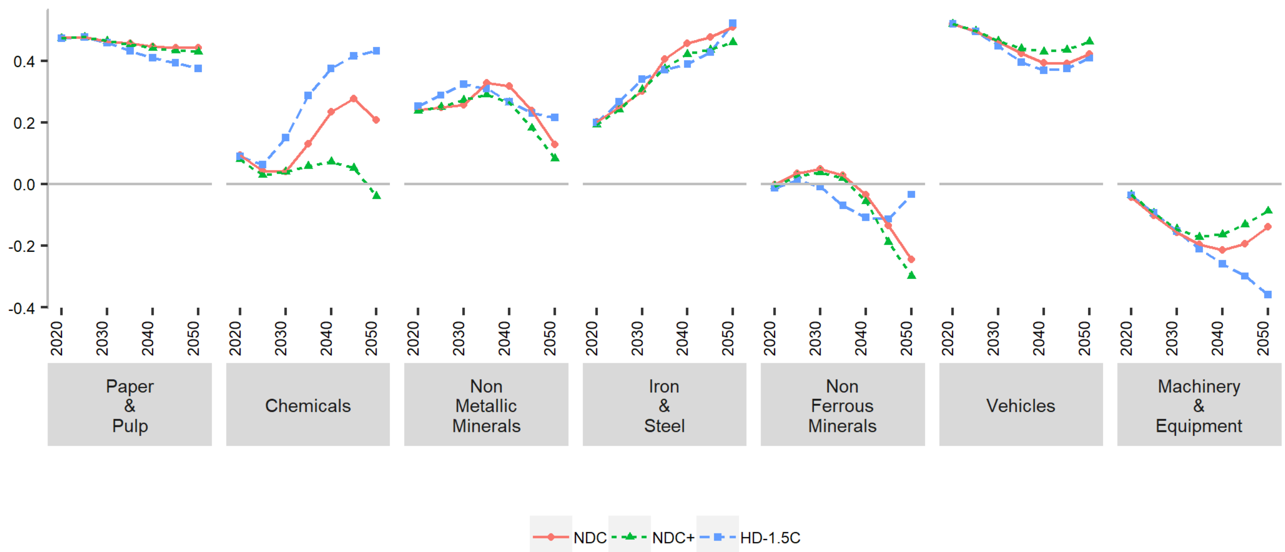

Figure 12: EU28: Relative competitiveness by industry

The potential effects on competitiveness can help identifying which industries could take the lead and support a more ambitious climate policy, and which ones could show some resistance against it. To illustrate this, Figure 13 compares the share of each EITE industry over total EU28 exports for 2011 (ICES base year) in the y-axis against the changes in relative competitiveness with respect to 2015 as a reference in the x-axis. This comparison in done for the medium run considering the changes of relative competitiveness in 2020 and 2030 for the three decarbonisation scenarios.

The importance of each industry's exports is represented in the y-axis and industries located towards the top would represent a higher share of EU28's exports. Then, industries located towards the right of the figure will show improvements in competitiveness while if they are located towards the left they will show a relative loss of comparative advantages in international trade. By looking at Figure 13, the Chemicals industry would be the one showing more resistance to a decarbonisation policy due to the loss of competitiveness which is also explained because it is amongst the most CO2 emitting industries in EU (see Figure 10) with an important share of EU28 exports (15%). The other industry with a relative

loss of competitiveness would be Non-Metallic minerals although it represents around 1% of EU28 exports. On the other side of the figure there are the industries that could take the lead within a decarbonisation policy such as Non-Ferrous Minerals, Iron & Steel and Paper & Pulp given that they would improve their relative competitiveness both in 2020 and 2030.

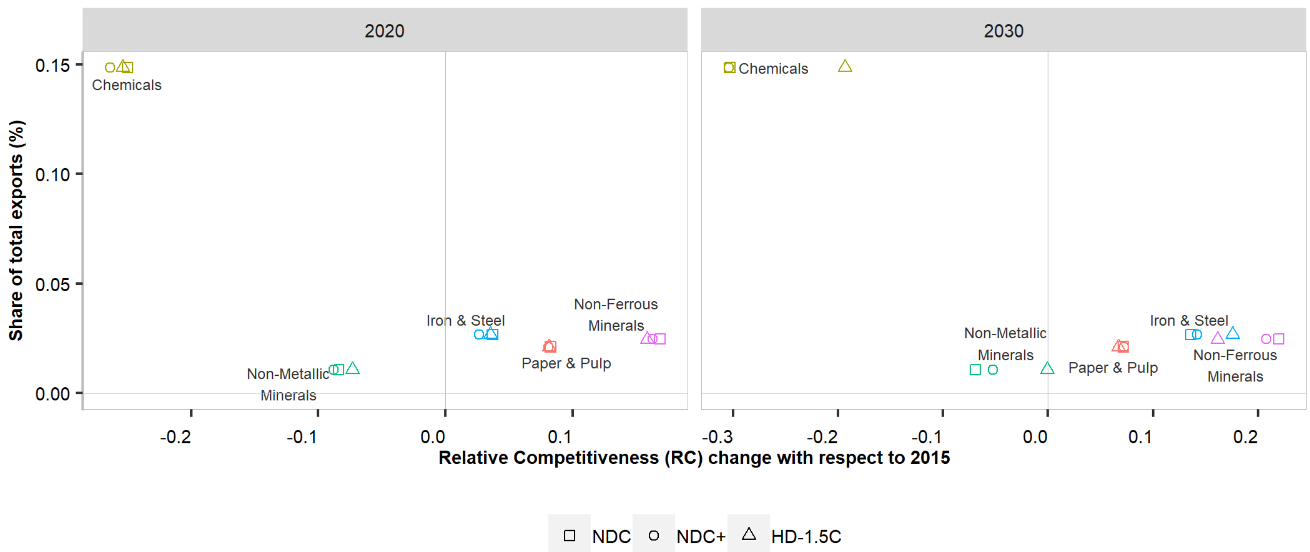

Figure 13: EU28: Change in relative competitiveness against national export share in 2020 and 2030

Within these last three industries, in which relative competitiveness improves in the decarbonisation scenarios; almost all European countries would show a positive effect as shown on Figure 41 of Appendix A. For the Iron & Steel and the Non-Ferrous Minerals industries, only the UK and the Eastern EU countries within Rest of EU28 would show a relative loss of competitiveness with respect to 2015. For the Paper & Pulp industry, only France and Germany could lose their relative competitiveness in 2030 depending on the scenario.

To conclude this overview, it is possible to indirectly draw some insights on employment by looking at the changes in the total labour costs that the ICES model provides by type of skill. Although, the ICES model does not reveal the changes in total labour stock given that the CGE framework assumes full employment, it is possible to shed some light on the reallocation of labour by looking at the total labour cost in each sector as depicted in Figure 14. The higher share of labour costs is devoted to skilled labour which at the same time is the type of labour showing higher variations in each scenario. While changes in 2030 are very small (see panel *a)* of Figure 14) as in the case of output, in 2050 the skilled labour cost varies much more in the Chemicals, Vehicles and Machinery & Equipment industries. In the Enhanced NDCs scenario where there is an increased ambition compared to the NDCs scenario, the less carbon intensive industries (Vehicles and Machinery & Equipment) increase the use of labour compared to the EITE industries. However, in the most ambitious scenario 1.5DG, the EITE industries (mainly Chemicals) increase more the use of labour along with that of capital.

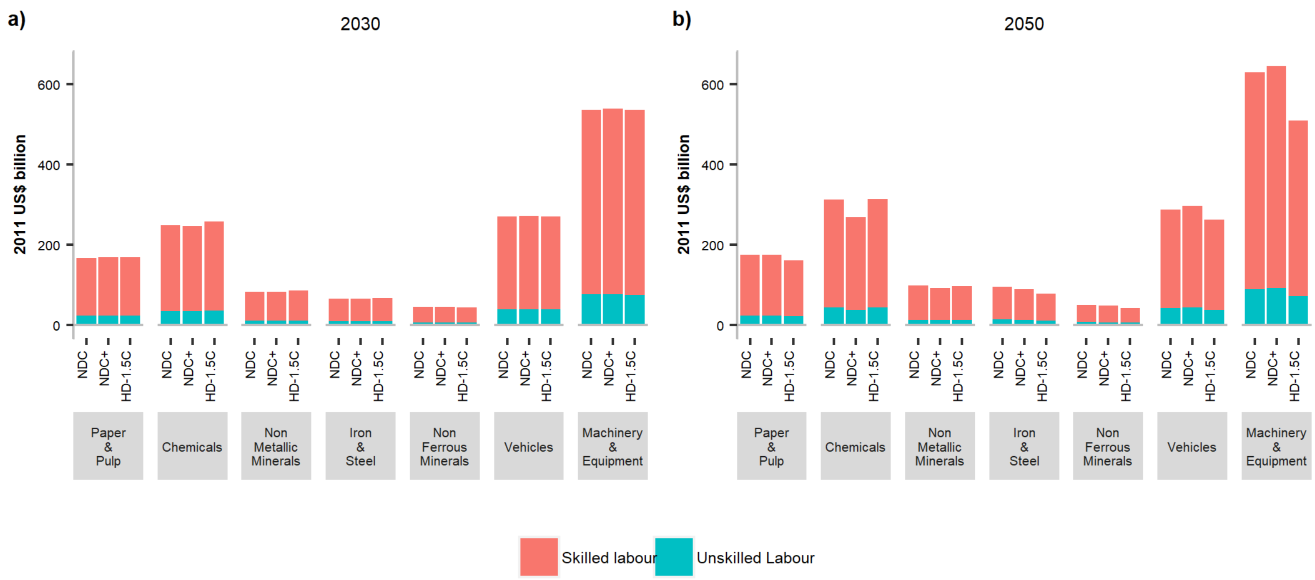

Figure 14: EU28: Labour costs by skill and industry for 2030 and 2050

6.2 Trade and competitiveness effects by sector

The relative position of a country or region in international trade is summarised in a straightforward way with two of the indicators introduced in section 2. The first one is the market share of world exports (*MS*) showing the relative importance of exports for each country. The second indicator is the Relative Competitiveness (*RC*) that compares the relative export and import advantages of a specific sector in a determined country, against the rest of the economy and the rest of the world. While the MS indicator gives more weight to export flows (and indirectly to larger industries) the RC indicator disregards the size of the economies since it compares exports and imports in relative terms. In other words, a country may be amongst the major producers of a commodity with a very high market share of exports but could be importing a lot as well which would lead a relative low (or even negative) value for the RC indicator. By plotting the Relative Competitiveness (*RC*) in the x-axis against the Market Share of exports (MS) in the y-axis it is easier to identify countries with higher relative competitiveness in each industry. Countries with a higher share (and size) of exports and higher relative competitiveness will be positioned at the upper right (or the right quadrant) of the plot, while countries with competitiveness disadvantages and lower export shares will be at the bottom-left of the figure.

6.2.1 Paper & Pulp

Figure 15 represents this information for the Paper & Pulp industry for three years. Panel *a)* presents all regions from Table 2 for 2011 which is the base year of the ICES model including the EU28 as an aggregate. This shows the initial position of each country/region before implementing all three decarbonisation scenarios. All European regions are highlighted in panel *a)* with a round marker to show their relative advantage/disadvantage in international trade. The EU as an aggregate region has a high market share (50%) as well as a relative competitiveness advantage. Germany, Italy, Spain and the rest of EU 15 show also a relative competitiveness concentrating 37% of world exports while France, UK,

and western countries in the rest of EU28 report a negative value for the *RC* index. According to the *RC* index, the industries with better performance in the rest of the world in 2011 were in the United States, Brazil, and South Africa.

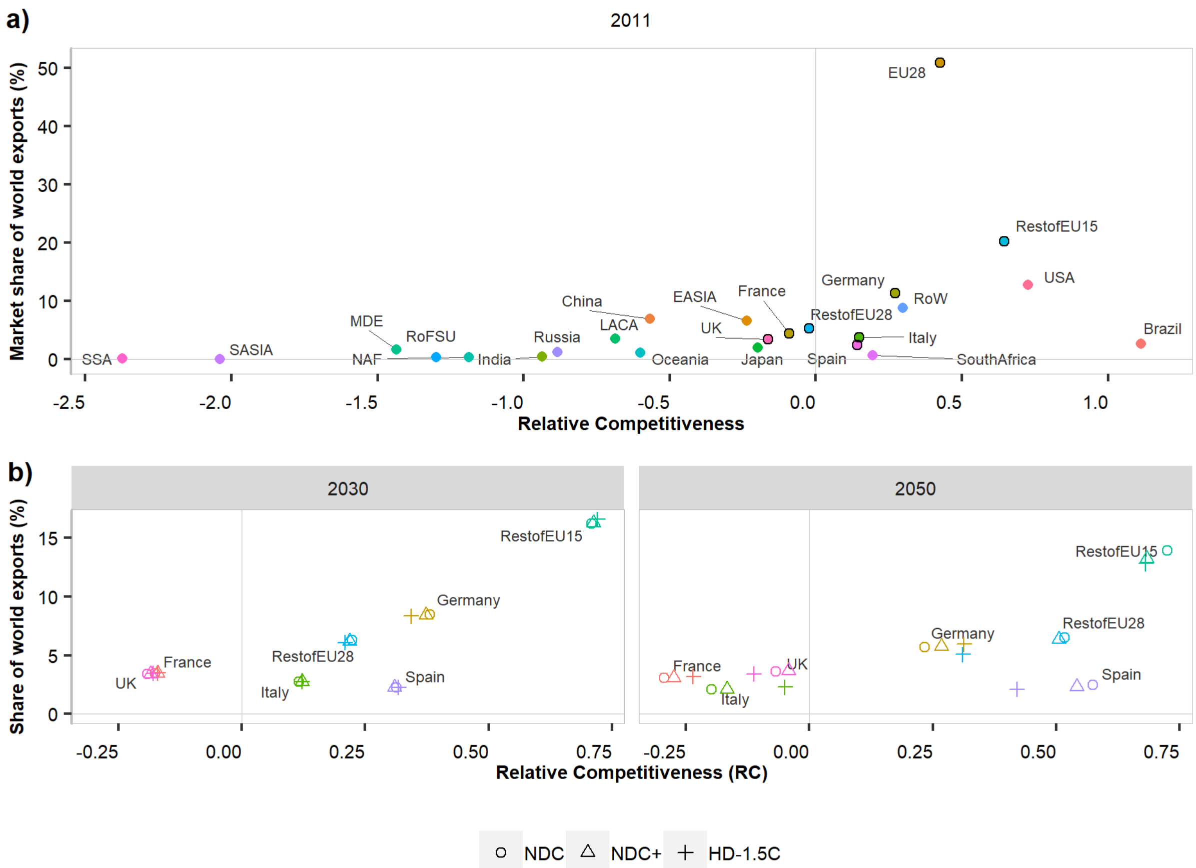

Figure 15: Trade and competitiveness in the Paper & Pulp industry

Panel *b)* of Figure 15 shows the same information for the three decarbonisation scenarios only for the European countries and for the years 2030 and 2050, with each scenario identified with a different marker, while sharing the same scales in the x and y axis. In this way it is easier to show the effect of each scenario on the trade and competitiveness indicators of each country. For 2030, the United Kingdom and France continue to hold a share around 3% of world exports, with their RC index being still negative and showing little differences among the decarbonisation scenarios. The rest of the countries in the right quadrant also show little differences within the scenarios, except for Germany that shows a slightly deteriorated competitiveness in the 1.5DG scenario. Only three regions show improvements in their competitiveness: the United Kingdom, Spain, and the Rest of EU28, this last region becoming more competitive when compared with its situation in 2011 (see also panel *b)* of Figure 27).

In 2050 there are more noticeable changes across scenarios and the most affected country would be Italy that would move to the left quadrant because of a decreasing competitiveness throughout the period which is more evident in the NDCs scenario. Spain and the rest of EU28 would be the winners in the industry since they move towards the top right of the plot, even though their competitiveness does

not improve as much in the 1.5DG scenario as in the NDCs-based scenarios. Finally, while Germany would lose gradually in the share of world exports and competitiveness results are better in the 1.5DG scenario.

6.2.2 Chemicals

For the Chemicals industry, the EU28 had a 45% of the world export share in 2011 and the main competitors from the rest of the world were East Asia, the Unites States, Japan, and India, as shown in the right quadrant of panel *a)* in Figure 16. Within Europe, Germany, France, UK, and the rest of EU15 show a relative competitiveness concentrating around 34% of world exports, while Spain, Italy, and the rest of EU28 show a null or negative RC index. In 2030 the relative competitiveness for the European countries is lower although in the 1.5DG scenario Germany, the United Kingdom, France and the rest of EU15 show a higher relative competitiveness in (see panel *b)* of Figure 16).

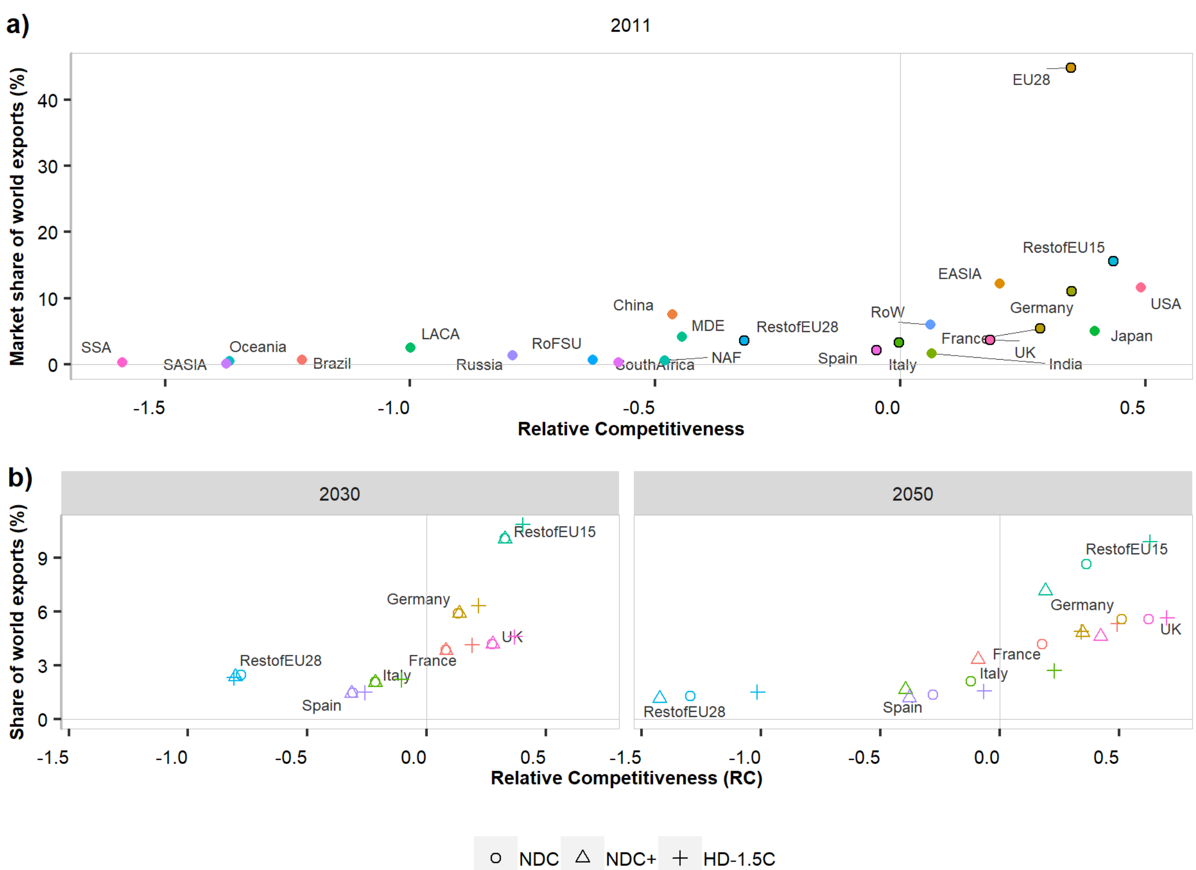

Figure 16: Trade and competitiveness in the Chemicals industry

In 2050 the increased ambition of the Enhanced NDCs scenario is detrimental for the competitiveness of all countries in contrast with the 1.5DG scenario. This would indicate that a more ambitious decarbonisation target in this sector should be accompanied by implementing energy savings from the

beginning along with an increased deployment of low carbon technologies available for power generation.

6.2.3 Non-Metallic Minerals

The Non-Metallic Minerals industry from the EU28 concentrated the 42% of world export shares and as an aggregate it retained a competitive position as shown on panel *a)* of Figure 17. The main exporters and competitors of the industry were in China, Japan, and India, while within Europe those with an advantage in competitiveness were Germany, Italy, and Spain concentrating 20% of world exports.

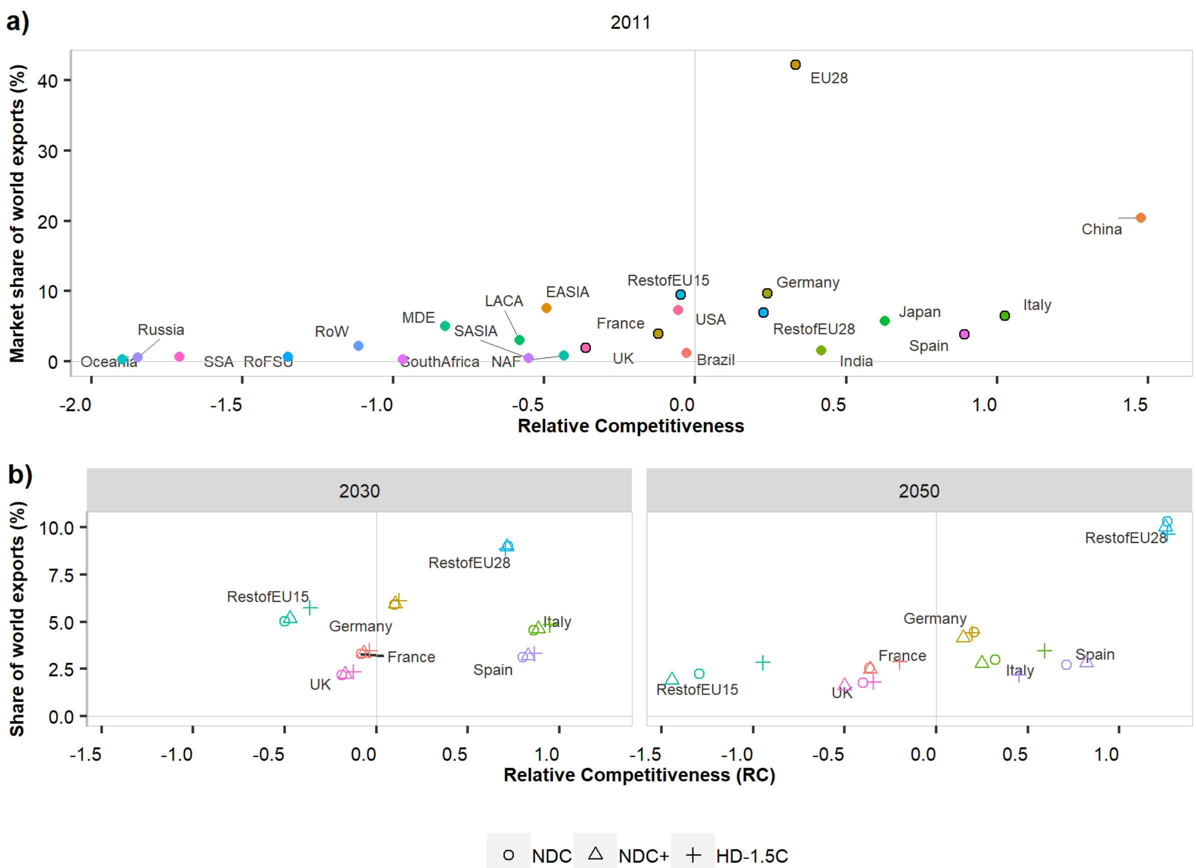

Figure 17: Trade and competitiveness in the Non-Metallic Minerals industry

Regarding the decarbonisation scenarios for 2030 (panel *b)* of Figure 17), there is not much difference across scenarios and almost all regions lose competitiveness (see also Figure 31 on Appendix A) with the exception of the rest of EU15 that would be better-off on competitiveness in the 1.5DG scenario. The region that improves the RC index is the rest of EU28 that in 2050 not only increases the share of world exports but also show an improvement of competitiveness in all three scenarios. In the case of this industry (being the most carbon intensive of Europe), increasing the ambition of mitigation targets as in the Enhanced NDCs scenario reduces competitiveness in particular for Italy, United Kingdom, and the rest of the EU15, while the opposite occurs when looking at the 1.5 DG scenario suggesting the

same conclusion as the Chemicals industry. A good strategy could be investing in energy efficiency at the beginning until low carbon technologies are deployed. On the contrary for the Spanish industry which was the most carbon intensive in Europe in 2011 (according to the GTAP database), the increased ambition of the Enhanced NDCs scenarios show better results than the 1.5DG scenario.

6.2.4 Iron & Steel

Iron & Steel is the second most carbon intensive industry in Europe (see panel *a)* of Figure 10). The EU28 produced almost 39% of world exports in 2011 and compared to the above analysed industries this is a more competitive market as represented in panel *a)* of Figure 18, with the major exporters being China, Japan, Russia, Brazil, and the United States. Within Europe, the main exporters that also have a relative competitiveness advantage are Germany, France, Spain, and the United Kingdom, while Italy and the rest of EU28 show a slight competitiveness disadvantage.

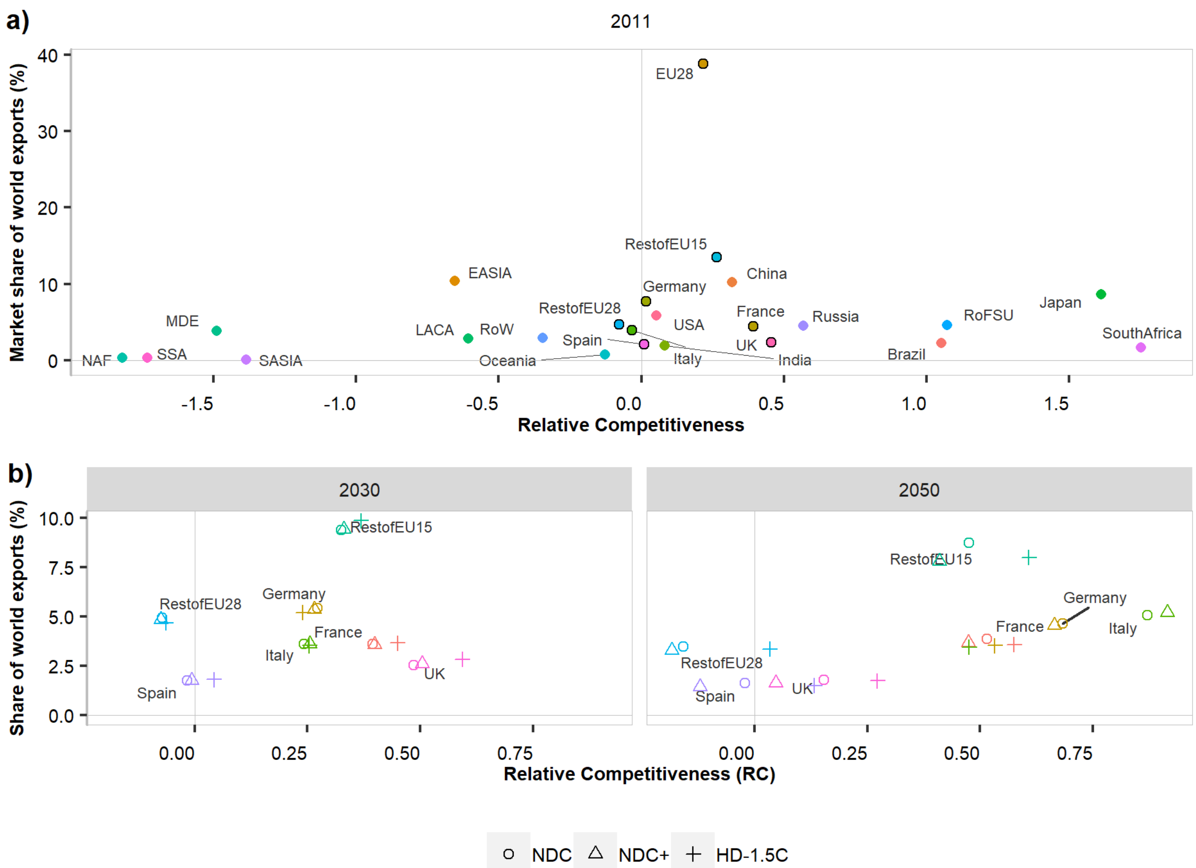

Figure 18: Trade and competitiveness in the Iron & Steel industry

As panel *b)* of Figure 18 shows for 2030, there are improvements in the relative competitiveness of Italy, Germany, and France, while Spain shows the opposite behaviour. Although there is not much difference with the NDCs-based scenarios, the 1.5DG scenario shows improvements of the relative competitiveness in France, United Kingdom, Spain, and the rest of EU15. However, it is in 2050 that there is a more differentiation across scenarios and for regions such as Italy and Germany that improve their competitiveness at a greater extent in the NDCs-based scenarios but not so much when global

efforts pursue the goal of 1.5°C. The opposite behaviour is shown by the rest of European countries since they would be better off in the 1.5DG scenario. While almost all European regions would improve their relative competitiveness, only the United Kingdom would see it deteriorated as also shown in panel *b)* of Figure 33 on Appendix A.

6.2.5 Non-Ferrous Minerals

The Non-Ferrous Minerals industry would be the most competitive industry from the seven analysed in this report, according to the RC indicator as can be appreciated in panel *a)* of Figure 19. In spite of providing 25% of world exports in 2011, the EU28 has a relative competitive disadvantage as an aggregated region. Only France and Spain have a positive *RC* index even though Germany has a high share of world exports (almost 7%). The main exporters and competitors in the world were the United States, Russia, South Africa, and Japan.

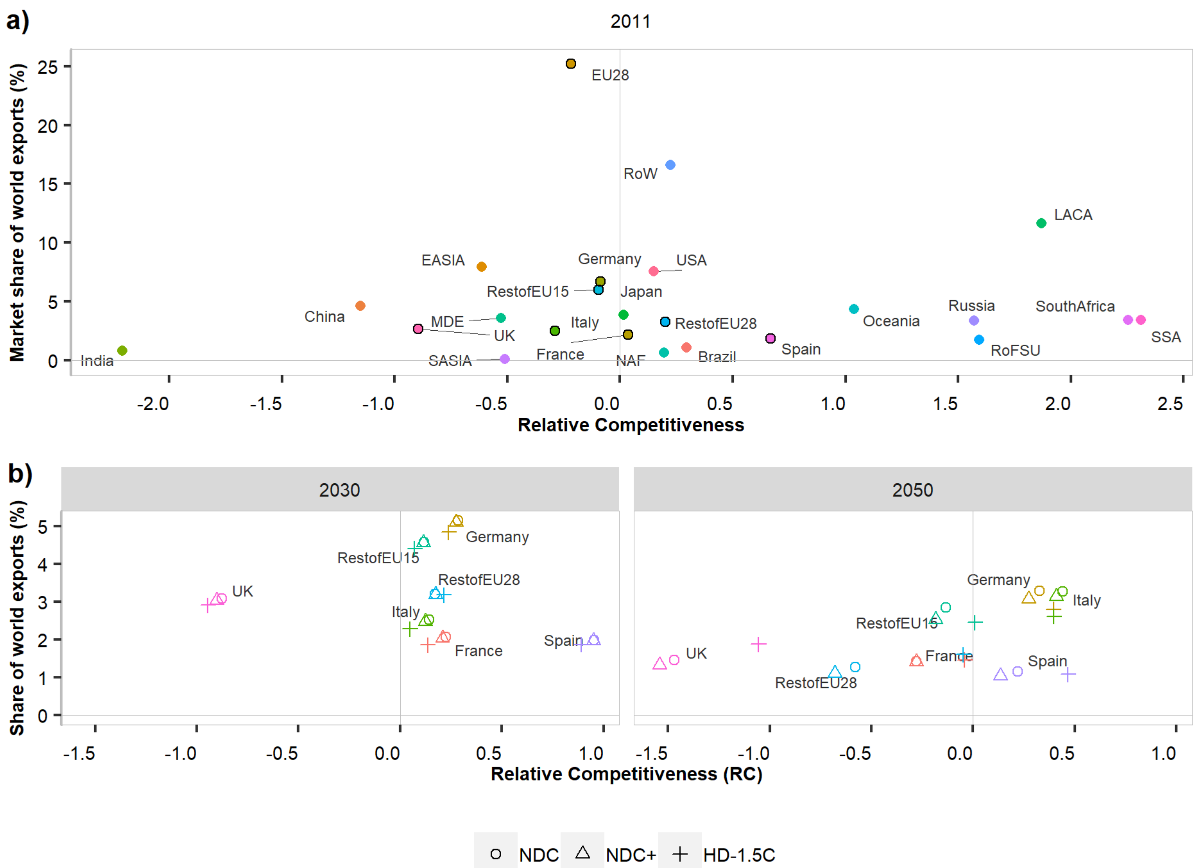

Figure 19: Trade and competitiveness in the Non-Ferrous Minerals industry

When comparing the position of an industry in 2011 shown in panel *a)* with panel *b)* of Figure 19 there is an improvement of relative competitiveness in 2030 for all European countries but the United Kingdom, with lower outcomes in the 1.5DG scenario compared to the NDCs-based ones. This situation is reversed in 2050 with almost all countries reducing their share of world exports and competitiveness, and only Germany, Italy and Spain show a positive relative competitiveness. In this case, as with the

other industries, there is a more noticeable differentiation across scenarios and the 1.5DG is the one that show better results in terms of competitiveness for all countries but Italy.

6.2.6 Vehicles

The major exporters of the vehicles industry in 2011 were Germany, the United States, Japan, France, and China, while the EU28 as an aggregate concentrated 48% of world exports. As shown in panel *a)* of Figure 20, the highest relative competitiveness index for 2011 is reported by Japan followed by Germany, France, and Spain. While the United Kingdom and Italy also have significant shares of world exports their relative competitiveness is negative.

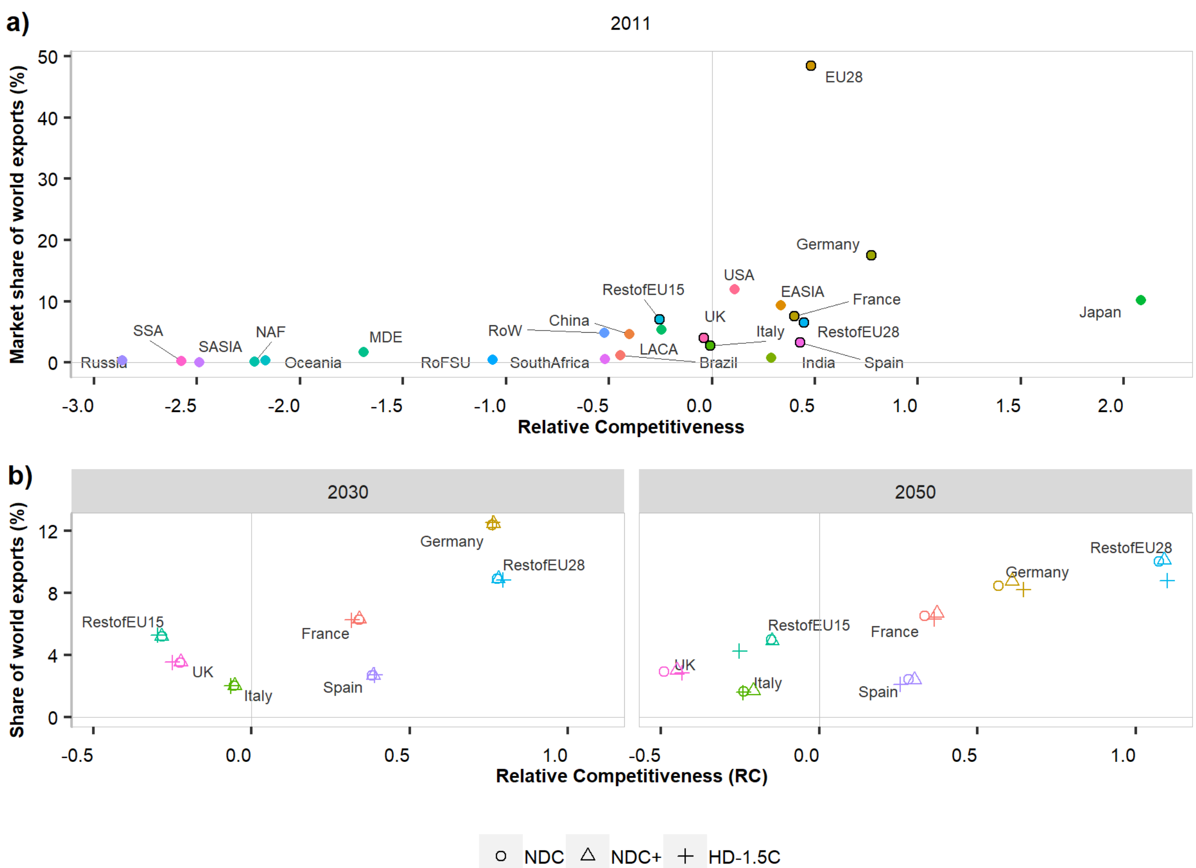

Figure 20: Trade and competitiveness in the Vehicles industry

The impacts of the decarbonisation scenarios are very similar in this industry in all European regions in 2030 (see panel *b)* of Figure 20) and almost all regions will see their competitiveness deteriorated compared to 2011 (see also panel *b)* of Figure 37 on Appendix A). In 2050 the difference across scenarios show better results in international trade for Germany and the United Kingdom in the 1.5DG scenario while for the rest of European countries would be better off in the Enhanced NDCs scenario.

6.2.7 Machinery & Equipment

For the Machinery and Equipment industry, the major exporters in 2011 were China, Germany, United States, and Japan as shown in panel *a)* of Figure 21. The EU28 provided more than 31% of world exports and the main European exporters with a positive relative competitiveness index were Germany, and Italy, while France, United Kingdom, and Spain report a negative relative competitiveness index.

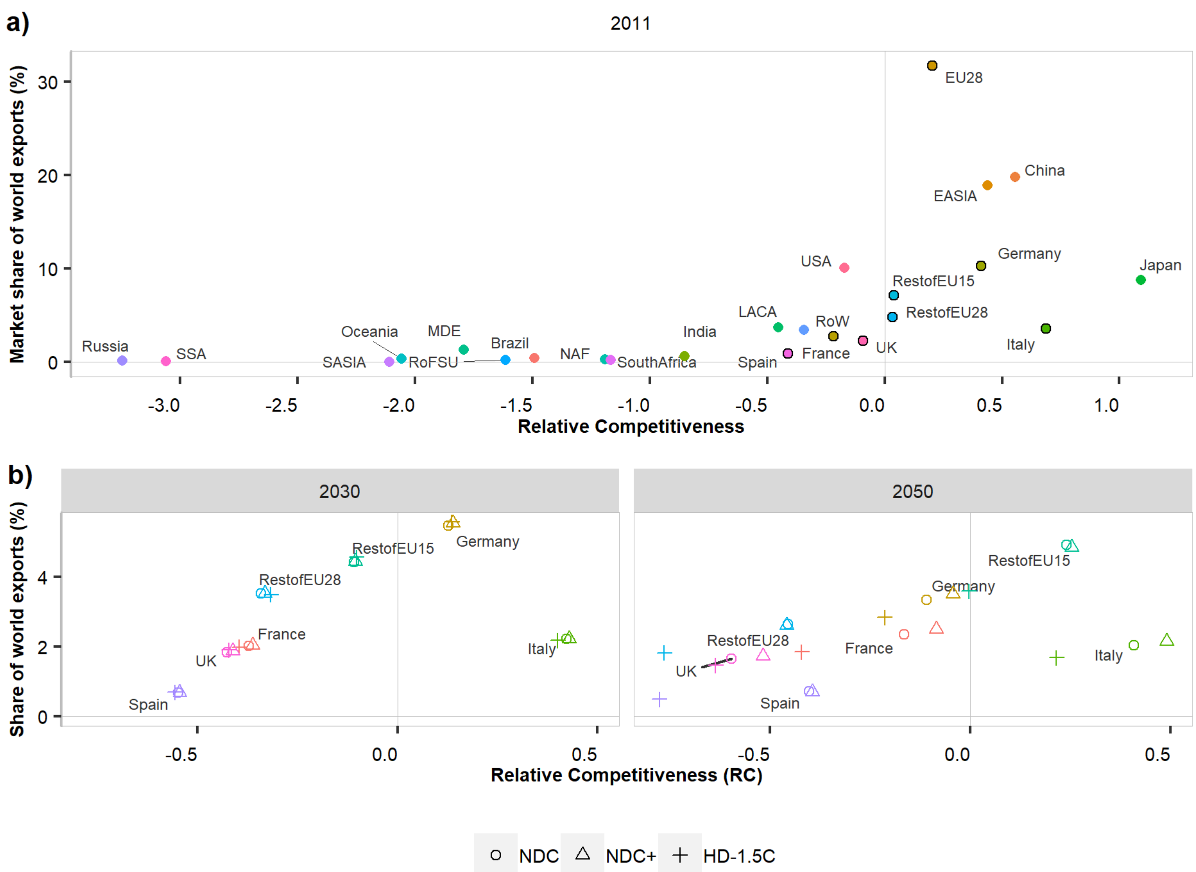

Figure 21: Trade and competitiveness in the Machinery & Equipment industry

For the decarbonisation scenarios represented in panel *b)* of Figure 21 in 2030, the differences across scenarios are little with a decreasing relative competitiveness in Germany, United Kingdom, Italy and the rest of EU28 (see also panel *b)* of Figure 39 on Appendix A). In 2050 these differences show better results in the NDCs-based scenarios for Italy, Germany, France, Spain, and the rest of Europe, while for the United Kingdom the 1.5DG scenario is closer to the Enhanced NDCs.

7 Impact of endogenous technological progress and R&D support policies on European industrial competitiveness in decarbonisation scenarios

Sections 4-6 have presented detailed sector-level estimates of industrial competitiveness impacts of decarbonisation scenarios provided by the ICES model. When considering issues related to industrial innovation and technical progress in general, the scenarios modelled with ICES relied on adjusting the assumptions related to exogenous technical change as well as relevant substitution elasticities as described in section 4. This section presents the results of a complementary modelling exercise based on the MEWA (Materials, Energy, Waste & Agriculture) model which is a dynamic stochastic general equilibrium (DSGE) model with endogenous technological change. Within MEWA, the companies may decide to invest in Research & Development (R&D) to unlock more efficient greenhouse gas mitigation options based on both market forces and regulatory framework instruments (e.g. carbon prices and R&D support for low-carbon innovation). While providing fewer details on the sectoral level and focusing on the EU, the modelling framework allows capturing the economic impact of innovation-based strategies of the industrial companies facing a sharp increase in carbon prices.

This section starts with a brief description of the MEWA model. It then presents decarbonisation scenarios, which differ not only in climate policy ambition but also in the potential of European industry to pursue low-carbon innovations. To provide insights about the impacts on competitiveness of decarbonisation in the presence of endogenous technical change, the modelling results focus on macroeconomic indicators as well as for sectoral indicators for the materials sector, which is the key focus of this chapter.

7.1 MEWA: a DSGE model with endogenous technological change

MEWA is a large-scale DSGE model. Similar to other general equilibrium models, it assumes that all markets (goods, labour, capital etc.) are in equilibrium in the steady-state so that a development on one market affects all other markets via price mechanisms. The agents in the model (producers, consumers etc.) act on the basis of their expectations both about the evolution of their own situation as well as future possible (stochastic) pathways for the whole economy. The shocks resulting from the introduction of new policies or other exogenous factors dynamically propagate through the economy, affecting the entire adjustment path of the economy to the new steady state. This feature allows MEWA to capture not only the ultimate impact of a given policy but also the whole process of economic adjustment over time. The model takes into account labour market imperfections, reflecting the delay in the reallocation of production factors (capital, materials and labour) across the sectors. In particular, the investment process is affected by the time required to replace existing capital with new, improved technologies (time-to-build). The policies in the model may be either anticipated by the agents or introduced as a (partial) surprise; in the former case, households and companies will adjust their decisions even before the introduction of the policy. For example, companies may anticipate a sharp increase of the carbon price in the coming decades and invest in the development of low-carbon technologies to prepare for new regulatory conditions or treat every increase in the carbon price as novel information revealed to them in the subsequent periods.

The main types of agents in MEWA include:

- Production firms which produce homogenous goods on the sectoral level employing capital, energy, labour and materials (raw and components). These are then differentiated by a monopolistic price setter and linked with imports using the sequence of Armington aggregator into the final products. Firms base their decision on cash flow (profit) maximisation;
- Households which supply labour, receive wages and capital income (as they are owners of firms and capital). Households base their decisions on utility maximisation, with utility stemming from the consumption of market goods and home production performed internally by unemployed or inactive family members,
- A government which imposes taxes, purchases public goods, subsidises research and development and undertakes infrastructure investments. The structure and level of both taxes and expenditures are exogenous (i.e. the government does not maximise social welfare with respect to shocks).

The most relevant feature of the DSGE modelling framework from the perspective of the research questions covered in this deliverable is its ability to model firms' decisions to engage in R&D investments, which in turn allows them to deploy capital and utilise other production factors more efficiently. R&D undertaken on the sectoral level affects the emission intensity of the installed capital gradually accumulating (capital embedded) knowledge on low-carbon technologies (Bukowski 2014). In other words, MEWA is capable of modelling endogenous, capital-embodied technological change. This includes the investment of industrial sectors in a new type of capital which allows to reduce or eliminate GHG emissions. The amount of private R&D investment is determined by cost optimisation, taking into account both market prices as well as regulations affecting carbon costs and/or providing direct R&D support to private companies. Furthermore, the emission efficiency of new capital is influenced not only by sectoral investment in R&D but also by total R&D investment as well as public R&D expenditure, reflecting spillover effects. More details on the production structure and technological progress in MEWA model are included in Annex D.

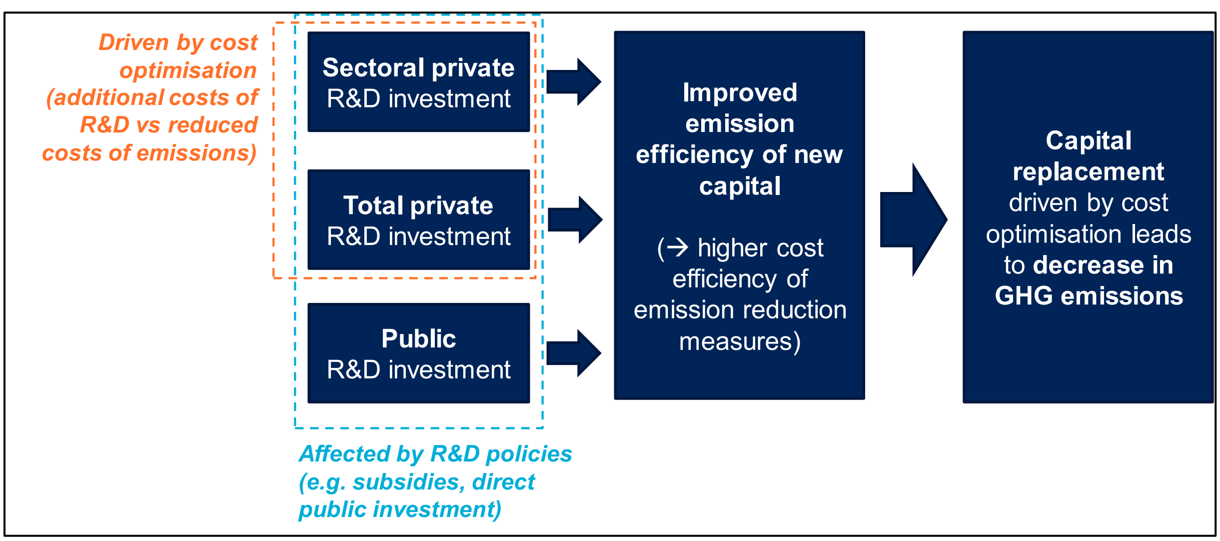

Figure 22: Endogenous technological change towards low-emission industrial capital in MEWA

The model input-output structure is estimated on WIOD database (see Timmer et al 2015), with 2014 set as a base year. The MEWA version employed for this modelling exercise covers two regions (EU and rest of the world) for the period 2010-2050, with policy shocks introduced starting in 2020. The following sectors are considered:

- Agriculture,
- Mining,
- Materials sector (basic metals, non-metallic minerals, chemical industry),
- Energy sector,
- Other industry and construction,
- Services.

Our modelling focuses on the materials sector. The sectors producing basic materials are among the most emission-intensive, and at the same time exposed to international competition. Moreover, the demand for their products is not directly linked to the energy transition required by climate policy (unlike in the case of the energy sector or fuel industry), although production costs are affected directly (emissions from fuel use and process emissions) and indirectly (emissions from energy sector) by carbon prices. Thus, companies in the materials sector may adjust to a low-carbon transition by modifying their production processes (including those related to fuel and energy use) to reduce emissions via investment in new types of low-carbon, capital-intensive technologies (e.g. CCS/CCU or hydrogen-based solutions).

7.2 Climate policy and low-carbon R&D availability scenarios

To capture the impact of endogenous technological change and its potential policy implications, we consider three types of R&D variants:

- **without R&D** – companies cannot invest in R&D to develop low-carbon capital,
- **with R&D** – companies can invest in R&D to develop low-carbon capital,
- **with R&D and subsidies** – companies can invest in R&D to develop low-carbon capital, a portion of carbon tax revenue (10%) is recycled to subsidise low-carbon R&D investments in materials sector.

The *R&D* as well as *R&D and subsidies* variants correspond to the ICES modelling scenario based on the assumption of the increased rate of exogenous technological change (section 5.2.2). There are two important differences, which make the modelling in this chapter complementary to ICES results: 1) An increased pace of technological change is introduced through the addition of an endogenous mechanism (ability of firms to invest in developing more efficient low-carbon capital) rather than adjusting the exogenous parameter determining the productivity growth of the selected technology, 2) the focus in MEWA modelling is on the availability of low-carbon capital directly deployed by industrial firms, rather than improvements in sources of zero-carbon energy.

The comparison of *with R&D* and *without R&D* variants allows capturing the role of endogenous technological change for the industrial competitiveness and macroeconomic outcomes, while the

difference between R&D variants with and without public subsidies for low-carbon innovations highlights the potential impact of industrial policy. Examples of such public subsidies on the EU level include the EU Innovation Fund financed through the EU-ETS system or co-financing from Horizon Programme for the projects focusing on low-carbon industrial innovations, both of which will be implemented in 2020s. Unlike the competitiveness protection measures discussed in section 1.3, such policies do not result in immediate, direct improvements of the European industrial competitiveness compared to the rest of the world. Supporting R&D activities which may result in gradual decrease in decarbonisation costs, however, may over time result in better performance of European industries in a carbon-constrained world.

Thus, the aim of the MEWA modelling exercise in this section is to explore to what extent the effects associated with the endogenous nature of technological change can affect the overall level of industrial competitiveness in the EU under different climate policy frameworks. To this end, the three types of R&D variants are combined with two climate policy scenarios with different level and distribution of climate policy ambition between the EU and rest of the world. These two scenarios are characterised by the same core assumptions as NDC+ and NDC+ DE scenarios modelled by ICES and described in section 4:

- ***Enhanced NDC, global effort (NDC+)*** assumes gradually increasing, uniform climate policy ambition on the global level, starting already in the 2020s.
- ***Enhanced-NDC, domestic effort (NDC+ DE)*** assumes that climate action is based on domestic efforts, with the carbon price in the EU remaining significantly above the average level in the rest of the world.

The policy scenarios are introduced via carbon tax pathways provided in table 4. The carbon tax pathways are calibrated in a way that the total carbon budgets are in line with the *Enhanced NDC (NDC+)*. In the model the CO_2 price and emission cap are interrelated allowing for alternative setting. Either the CO_2 path is provided exogenously resulting in a certain emission level for every year and total carbon budget in a given period or the emission cap is set on an exogenous level with CO_2 prices adjusting endogenously in the model. In the case of this piece of research we used the former approach controlling for the results to be in line with the carbon budgets produced by the ICES modeling.

Table 4: Carbon tax in MEWA scenarios, USD 2015/tCO_2

	Enhanced NDC, global effort (NDC+)						
	2020	***2025***	***2030***	***2035***	***2040***	***2045***	***2050***
EU-28	15	35	65	110	160	225	300
Rest of the world (average)	15	35	65	110	160	225	300
	Enhanced NDC, domestic effort (NDC+ DE)						
	2020	***2025***	***2030***	***2035***	***2040***	***2045***	***2050***
EU-28	20	60	120	200	300	420	560
Rest of the world (average)	10	30	60	100	150	210	280

All scenario modelling results are presented as a deviation from the baseline scenario, which assumes no carbon pricing and no possibility for the companies to invest in low-carbon R&D. GDP growth in the baseline scenario is calibrated to match the SSP2 pathway.

7.3 Modelling results

On a macroeconomic level, all six decarbonisation scenarios achieve a deep decarbonisation of the European economy (over 50% reduction in CO_2 intensity), with moderate GDP loss (-0.8%-2.1%), a significant shift in expenditure from consumption to investment and net exports outcomes depending on whether the global emission reduction efforts are uniform or diversified (see Figure 23).

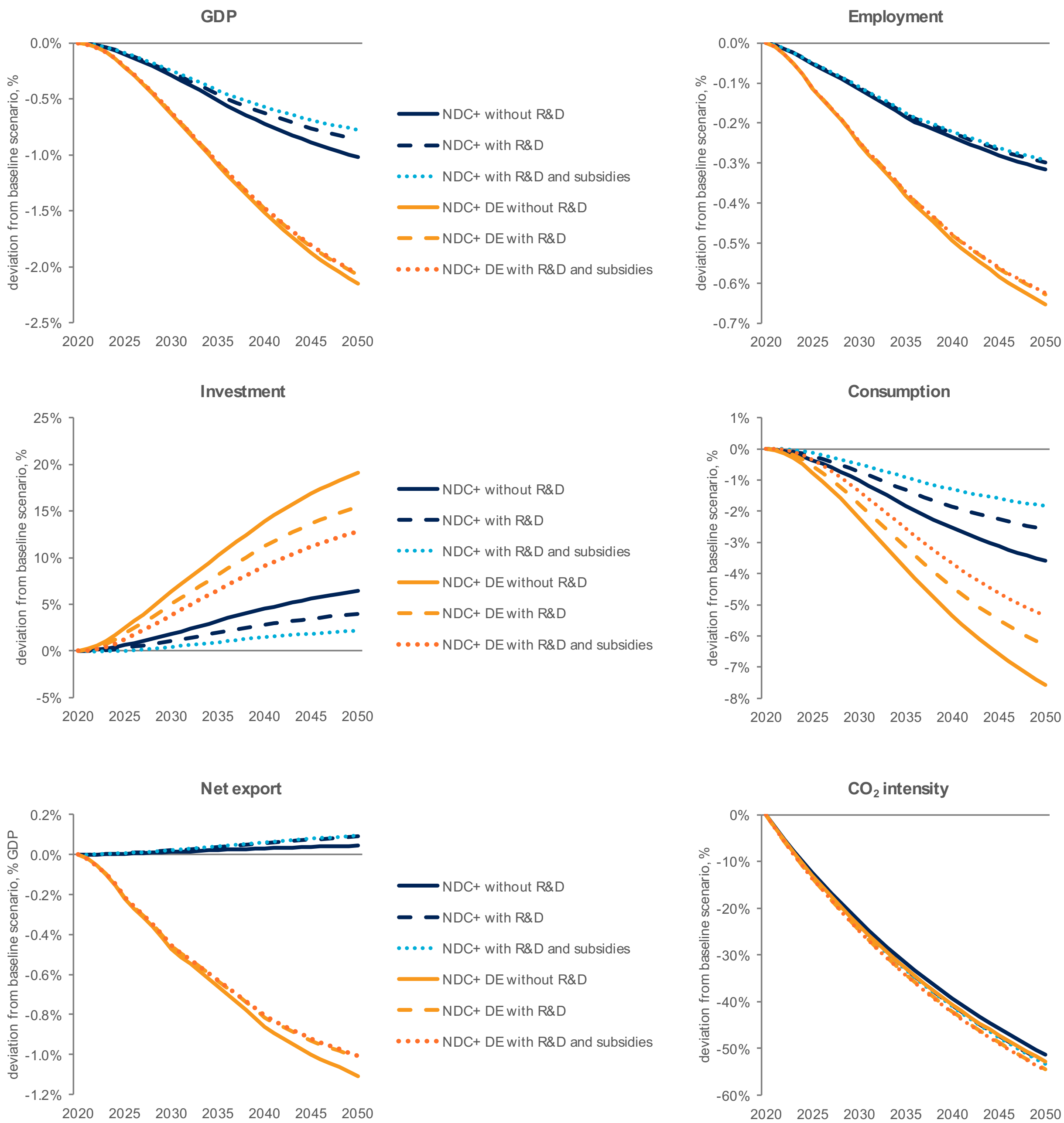

Figure 23: EU28: deviation of macroeconomic indicators relative to the baseline scenario

Accounting for endogenous technological change and potential R&D subsidies for low-carbon innovations has the most significant impact on the aggregate investment and consumption levels.

Capability to develop cheaper low-carbon capital reduces the scale of the decrease in consumption required to provide resources for deployment of mitigation measures. Hence the investment in low-carbon R&D leads to smaller GDP declines relative to the baseline scenario as well as small improvements in net exports and deeper CO_2 mitigation. Nevertheless, neither firms' pursuits of low-carbon R&D activity nor significant public support for R&D investment can offset the negative impacts of the differentiated climate action on the EU economy. The reason lays in the graduality of the innovation process that cannot react fast enough to the large carbon price shock delivering the appropriate reduction of costs of the low carbon technologies. The cost of domestic production grows, affecting the relative terms of trade between the EU and the rest of the World and the trade balance, especially in the export or import intensive sectors. While in NDC+ scenario the EU net export slightly increases, in NDC+ DE its decline is greater than 1% GDP. Accounting for endogenous technological change and R&D subsidies offsets only 0.1% GDP of the decline.

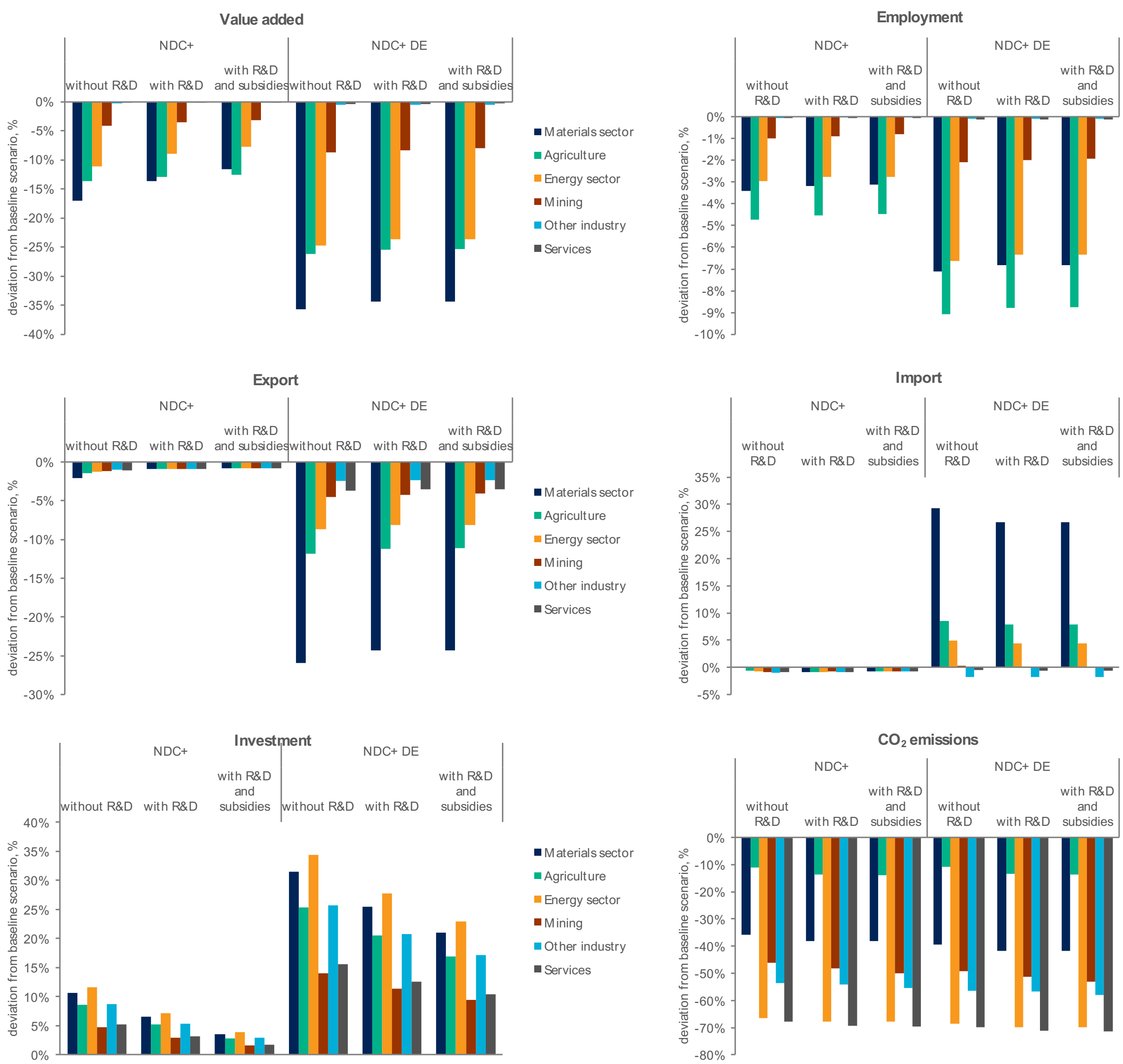

Figure 24: EU28: deviation of sectoral indicators relative to the baseline scenario in 2050

Materials sector, which accounts for 2% of the EU GDP, is among the sectors most affected by climate policy. In all scenarios considered, it sees the largest decline in its international competitiveness (measured by shifts in trade flows) among the sectors modelled (see Figure 24). In most scenarios, the deepest decline in the value added compared to the baseline occurs in this sector. The only exception is NDC+ with R&D and subsidies: in this scenario, the decline in the energy sector is slightly larger than in the materials sector that exploits its larger R&D potential. Producers of basic materials also see the second-largest decline in employment, and the increase in their investments is only slightly lower than in the energy sector. At the same time, the emissions in the sector are relatively hard to abate, which results in smaller CO_2 declines compared to most of the sectors, except agriculture.

Overall, while decarbonisation scenarios significantly affect materials sector, agriculture, energy and – to a lesser extent – mining, their impact on competitiveness of other industries and services (which account for more than 75% of European GDP) is moderate, despite significant increase in the investment effort and deep CO_2 emission reductions achieved in these sectors. This is due to their relatively low exposure to carbon prices, the reallocation of labour from more affected sectors and the increased demand for investment goods from the more affected parts of the economy. At the same time however the overall labour supply decreases as the revenues from CO_2 costs are recycled to the economy in a form of social transfers negatively affecting the economic activity of households and employment level in all sectors. In the materials sector, accounting for the endogenous technological change has the largest impact on the level of its investment effort. R&D activities supported with public subsidies lead to a significant reduction of the cost of low-carbon capital deployment: thanks to R&D incremental investment effort declines from 11% to 4% in NDC+ scenario and as much as from 31% to 21% in NDC+ DE scenario. A similar effect is present in the energy sector (also affected by rising CO2 prices) and the rest of the industry that responds to the larger demand on investment goods from these parts of the economy that face larger costs of CO_2 emissions and increase their investment spending. Even without increased R&D larger investments allow for the indirect improvements of European firms' competitiveness compared to the rest of the world, mitigating the overall negative impact of the low-carbon transition on the European economy. This effect is present in all scenarios and is especially prominent in the scenarios with low costs of capital intensive, low-carbon investments i.e. in the scenarios with prominent R&D activity.

Looking at value added, the innovation-based decarbonization actions by companies in the materials sector is more effective in the NDC+ scenario (see Figure 25). They allow mitigating the decline of value added relative to the baseline by a third (5 percentage points), while for the NDC+ DE scenario the decline is only 1 percentage point smaller after introducing R&D and subsidies. The impact of the endogenous R&D efforts on emission reduction is indirect. Research activity reduces the price of new low-carbon technologies allowing for faster decarbonisation with lower monetary costs. At the same time, domestic R&D efforts contribute to the global stock of knowledge invoking a positive externality on low-carbon innovations both domestically and abroad. This means that the low-carbon capital cost in the EU depends both on local and global research efforts and therefore, indirectly, on the CO_2 prices in both regions. In the NDC+DE scenarios the emission reduction in the EU is larger (compared to the NDC+ scenario) because of the prevalence of a domestic mitigation effort translated in a higher CO_2 price on the EU market, however in the rest of the world it is lower (as the global stock of low carbon knowledge is lower, and low-carbon capital is – ceteris paribus – more expensive). Therefore, the MEWA model suggests that it is cheaper to deliver the same reduction of global emissions when the

efforts are coordinated. In the R&D scenarios this induces a faster decline of the low-carbon investment costs and smaller drop of GDP, requiring smaller inter sectoral reallocation on the labor and capital markets. The availability of R&D options slightly improves international competitiveness of the European materials sector in both NDC+ and NDC+ DE scenarios. In the case of an equal global effort, it virtually eliminates the deviation from the baseline for both exports and imports. If the mitigation effort is significantly higher in the EU, however, the negative competitiveness impacts of a higher carbon price difference are too high to be compensated by the availability of low-carbon innovations: accounting for R&D compensates only about 10% of the decline in exports and increase in imports of materials sector production compared to the baseline scenario.

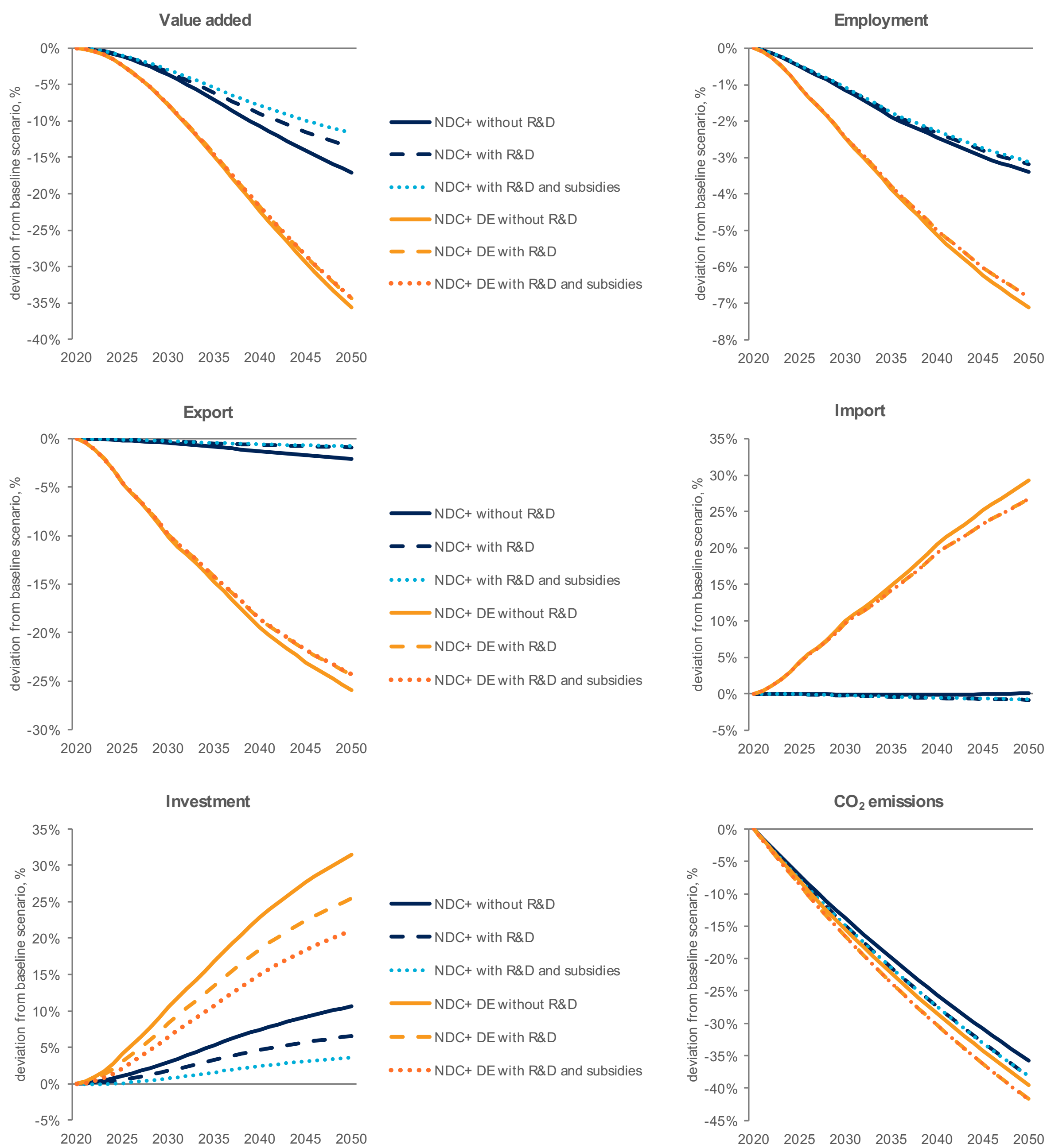

Figure 25: EU28: deviation of sectoral indicators for materials sector relative to the baseline scenario

The modelling results suggest that accounting for endogenous technological change significantly affects the estimates of the decarbonization costs and benefits both on a sectoral and macroeconomic level. In particular from the perspective of households which have to sacrifice some portion of their consumption to provide resources for the mitigation efforts across the economy the ability to innovate and undertake the coordinated international mitigation effort is of key importance. Allocating some of these resources in R&D efforts by companies and the public sector leads to more availability of cheaper mitigation options (more efficient low-carbon capital) in the later stages of transition, which limits the decline of overall GDP (through improved competitiveness and productivity on the sectoral level) and mitigates the required consumption drop on the macro level. This provides additional rationale for supporting R&D in low-carbon innovation. At the same time, MEWA modelling results suggest that in a world on differentiated mitigation efforts, relying on low-carbon industrial innovation alone is not enough to protect the competitiveness of the European emission-intensive industries. The scale of competitiveness decline caused by an unequal mitigation burden consistent with deep emission reduction pathways is too large to be offset by technological improvements in the EU industry; additional policy instruments are required to achieve these goals, such as implementing policy measures to address competitiveness concerns or forming international climate clubs, as explored by ICES modelling in section 5. At the same time, important synergies can be achieved through a combination of low-carbon R&D support with policy frameworks which do not result in significant differences of carbon pricing affecting trade flows: the positive impact of low-carbon innovation on sectoral value added is greater, additional investment requirements are lower, while emission reductions are deeper.

8 Conclusions

This deliverable presents an analysis of trade and competitiveness indicators at the sectoral level, focusing on Europe, and using three explorative scenarios that illustrate the Paris Agreement long-term goals. The analysis of decarbonisation scenarios takes into account some policy options to address competitiveness concerns, as well as industrial policies in a climate policy context. All scenarios have been implemented in a recursive dynamic multi-region and multi-sector CGE model, considering three decarbonisation elements: energy efficiency improvements, the deployment of electricity as the main source of energy, and the decarbonisation of the power generation system. These elements vary in intensity for each of the three decarbonisation scenarios reflecting the level of ambition in curbing emissions by 2050.

The first part of the analysis considers a decarbonisation scenario where the mitigation efforts are carried out domestically with differentiated carbon prices in each region, while only EU countries share a common carbon price within the EU-ETS. This scenario setup allows for the analysis of two alternatives, which could be implemented in the EU to address competitiveness concerns related to climate policies for EITE industries: Border Carbon Adjustments (BCA) and Output Based Rebates (OBR). Both measures show a positive effect on industrial output and competitiveness, but their effect is decreasing over time as the economy becomes highly decarbonised. Results suggest that BCA have a short-term effect in mitigating competitiveness losses. While OBR, which would allow industries to improve their situation in the long-term by investing the rebate in more energy efficient capital and low carbon energy sources, shows more effective and lasting results. Only highly carbon intensive EITE industries benefit from both BCA and OBR. However, if a global ETS were put in place, all EU EITE industries would be better off as they could buy permits abroad to offset emissions, and therefore produce more output. On the contrary, when the mitigation efforts are carried out domestically, the carbon price in the EU is much higher, leading to the deployment of more efficient technologies and low carbon and renewable energy sources within the region.

In fact, technology deployment and innovation will play a crucial role in decarbonising the economy at the EU and world levels. If the rate of technological innovation and technical progress of renewable energies increases, this would also benefit EITE industries - due to a wider availability of low carbon technologies, thus improving competitiveness and production in industries that need to decarbonise their production processes.

To understand the contribution of international cooperation in a climate policy context we included the possibility of creating coalitions - based on literature discussing the advantage of mitigating emissions in a coordinated effort through the establishment of climate clubs. Our analysis focused on four characteristics that can be simulated in a climate club: i) a more active technology transfer (through import-driven spillovers) between members, ii) free trade agreements to liberalise trade in key industries, iii) reducing the cost of capital for renewable energy deployment, and iv) imposing tariffs to imports from regions outside the coalition. In this example, the climate club is formed by the EU28, Japan, China, India, and Brazil. The technology transfer and reduction of capital cost for renewable generation would benefit countries such as India and Brazil - improving their relative competitiveness, exports, and output - with small effects in the rest of the coalition and some negative effects on Japan and Germany. However, not all countries would benefit of this coalition setup in terms of competitiveness. This suggests that club incentives should take into account the individual

characteristics of members to identify not only their potential benefits but also the risks and costs of abiding to the club. In this regard, extending the FTA to all EITE industries could produce better results for the coalition. A trade liberalisation of EITE industries is advantageous for all members in terms of production and exports with the only exception of Japan. Conversely, imposing tariffs on Iron & Steel imports from outside of the coalition would improve production, exports, and competitiveness of all club members.

The second part of the analysis presented in section 6 does not explore the possibility of a differential treatment for EITE industries. The intention is to provide a general picture of the decarbonisation scenarios, which are implemented assuming a coordinated effort with a global ETS and a uniform carbon price. It represents a hypothetical situation in which there would be no need for policies to level the playing field for EITE industries.

Compared to the NDC scenario, in which there is no increased ambition before 2030, raising the mitigation target before 2030 in the NDC+ scenario would have little effect on production and employment in the industries analysed, while the competitiveness indicators also do not differ much between both scenarios. By 2050 the situation will be similar for most industries, except for Chemicals which would show a lower output and a deteriorated competitiveness. A similar situation would happen for the Iron & Steel and Non-Ferrous minerals industries, although with slightly lower output, employment, and competitiveness levels. Conversely, industries related to Vehicles, Machinery and Equipment would increase their output since they are less carbon intensive. Energy use will increase thanks to the deployment of renewable energy, which is also spurred due to the signal provided by the carbon tax.

When the mitigation targets are aligned to a long-term objective related to 1.5°C increase in temperature by the end of the century, the trade and competitiveness effects on the medium-term (2030) would be very similar to the NDC-based scenarios, and in some cases could perform even better. This is explained by the measures which are assumed to be put in place, such as an accelerated deployment of clean and renewable energies, along with energy efficiency improvements, plus the global ETS. With the opportunity to shift the mitigation effort abroad, to industries with lower marginal abatement costs, EU industries would be better off buying emission permits abroad. Moreover, this scenario implies a decarbonisation pathway based on the reduction of final demand and higher technological progress, with a level of output by 2050 that would be lower than in the NDCs-based scenarios, which is achieved with an almost decarbonised energy system. This implies a more efficient economy and that some industries would be able to increase their competitiveness thanks to a higher availability of low carbon energy.

The industries that could show a higher resistance to mitigation policies are Chemicals and Non-Metallic Minerals given that they would see their relative competitiveness reduced in the decarbonisation scenarios analysed over time. The Chemicals industry held 15% of EU exports in 2011 (base year of the ICES model) showing its importance in international trade. In addition, it is among the most emitting EITE industries and relies on a high share of fossil fuels, which explains why it could face difficulties in a transition to a low carbon economy. This is confirmed by the reduction of output in 2050 could suffer to comply with the corresponding mitigation actions required to keep emissions within the specified carbon budgets of the decarbonisation scenarios. In fact, in the medium-term (2030) when the

reduction targets are not ambitious yet and there is the possibility to buy emission permits, the industry can maintain production levels without being affected by an increased mitigation goal.

Conversely, other EITE industries such as Paper & Pulp, Iron & Steel and Non-Ferrous Minerals could improve their competitiveness compared to levels before the implementation of climate policy (2015). Within EITE industries, the countries that could lose competitiveness compared to 2015 levels are the United Kingdom and the Rest of EU28 (for Iron & Steel and Non-Ferrous Minerals), and France and Germany (for Paper & Pulp).

Results at the country level show which industries could be more or less affected in each scenario. For example, the Paper & Pulp industry in Italy and France would improve trade and competitiveness in scenarios with more ambitious mitigation efforts, given that it is less carbon intensive compared to other EITE industries. For Chemicals, German trade and competitiveness would be affected, while in the Non-Metallic Minerals, Italy, France, and UK would improve their trade indicators. In the case of less carbon intensive industries, only Germany and France would show an improvement of relative competitiveness in the vehicles industry.

The importance of industrial innovation policies is confirmed by the analysis in section 7, which provides the results of DSGE modelling with endogenous technological change representation. The analysis finds that technological progress enabled deep decarbonisation is not purely exogenous, but rather affected by the decisions of private and public sector to invest in development of low-carbon innovations, incentivised by policy and market signals. This implies that providing a long-term carbon price signal motivates companies to invest in developing more efficient low-carbon capital. The public sector can further support this process by directly investing in R&D in the area of industrial decarbonisation, as well as providing additional incentives for private projects. This can significantly affect the long-term cost of transition, especially from the perspective of decreased needs to redirect expenditure from households' consumption to incremental low-carbon industrial investments. However, the modelling results for scenarios that assume higher mitigation effort in the EU show that investment in R&D cannot on its own offset the loss of competitiveness and decline in economic activity in emission intensive European industries. At the same time, R&D activities and associated public support schemes are more efficient in a world with more equal climate policy ambition. This implies the need to combine support for low-carbon innovation with policy instruments which directly address competitiveness concerns, such as BCA,OBR (discussed in section 5.1) or international cooperation, which could also be in the form of climate clubs (as discussed in section 5.2.3).

While this study offers insights on the trade and competitiveness effects on decarbonisation scenarios produced with general equilibrium models (CGE and DSGE), there are some caveats worth considering to correctly frame the results and implications of the analysis. From the modelling point of view, the degree of detail in which a specific industry can be represented relies on national accounts data depicting the structure of the industry at the national level. In contrast, more detailed partial equilibrium (PE) models can consider specific technologies and characteristics at the firm level. However, the advantage of the GE models over PE models is that they can consider intersectoral and international trade flows, which are key to analyse the effects of climate policies on trade and competitiveness. Therefore, this kind of assessment should be complemented with more detailed studies of the specific industrial production processes already available for EITE industries.

Another caveat derives from assumptions made to build each decarbonisation scenario, as described in section 4. These assumptions have been made considering previous decarbonisation studies and are based on two enabling conditions for a successful decarbonisation pathway. The first one refers to early action to implement energy efficiency measures, which would be key for EITE industries to begin emission reductions. The second one refers to a successive phase of development and deployment of low carbon technologies, which would allow industries to reduce the dependence on fossil fuels and boost their production without emitting greenhouse gases. This is corroborated by the example of increased renewable energy deployment to support industrial energy requirements at more affordable costs.

9 References

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10 Appendix A: Trends on trade and competitiveness by sector

This Appendix summarises results for the selected industrial sectors with a focus on trade and competitiveness indicators as described in section 2, giving details for some EU countries and regions. To analyse the trade dimension three indicators have been selected. The first one is the market share of world exports (*MS*) to understand the importance of each commodity export in world trade. This is complemented with a second indicator which is the ratio of net exports to output (*NXY*) to see if the industry is a net exporter and how important are net exports in terms of domestic production. The third indicator is the ratio of world price to export price indexes (*WPXPR*) to confirm whether the improvement in exports is due to a decrease in this price ratio, given that an export price index decreasing at a higher rate that the world price index would indicate an increased competitiveness of that sector thanks to lower relative prices. There are also three indicators related to comparative advantages and competitiveness. Two of them draw on the concept of revealed comparative advantage computed using only export data (*RCA1 – Exports*) and using export/import data (*RCA2 – Export/Import*), while the last indicator is the Revealed Competitiveness (*RC*) that provides information of the performance of the sector compared to the rest of the economy and the rest of the world. To give an idea of the past trends of these indicators we include data for 2004, 2007, and 2011 using historical data from the GTAP database (Aguiar et al 2016) which is available at the same granularity of the ICES regions. Afterwards, all simulation results are presented from 2015 to 2050 in 5-year time-steps.

10.1 Paper & Pulp

This is the least carbon intensive from all EITE industries as shown on Figure 10. The market share of world exports for the EU28 was around 55% for 2004 which decreased to 50% in 2011, from which Germany holds 11%, followed by France, Italy, UK and Spain with an aggregate share of 14%. The EU28 shares decline in the to around 35% by 2050 as shown in panel *a)* of Figure 26. The ratio of net exports over imports would increase and the effects of more ambitious abatement target shows clearly after 2030 in the NDCs-base scenarios and after 2020 in the 1.5DG scenario (panel *b*). This behaviour is explained also by the relative changes in exports prices against world prices (panel *c*). Since export prices decline faster that world prices, then the region exports more of that commodity. Finally, the competitiveness indicators of the region remain relatively stable from 2020 on with a slightly lower results in the Enhanced NDCs scenario and much lower in the 1.5DG as shown in panels *d)*, *e)* and *f)* of Figure 26. It is important to note that the indicators that consider also the import flows (*RCA2*) and the comparison with the rest of the world and the economy (*RC*) indicate a clear difference across scenarios with a much more diminishing trend.

While Figure 26 refers to the trade and competitiveness indicators for the EU28 in aggregate, Figure 27 shows the evolution of the market share of world exports for seven EU28 countries and macro-regions along with their trend of relative competitiveness. The regions that would improve their competitivity based on an increasing *RC* index are Spain, rest of EU15, rest of EU28, and the United Kingdom despite having a relative comparative disadvantage in exporting pulp & paper due to a negative value for the *RC* index. This implies that Spain and the rest of EU would maintain a relatively stable share of world exports while countries like Germany and Italy due to a decreasing trend in relative competitiveness

would reduce their share of world exports, in particular in the NDCs scenario represented with a red line in panel *b)* of Figure 27 which is explained by the need to intensify efforts to comply with the carbon budget set until 2050.

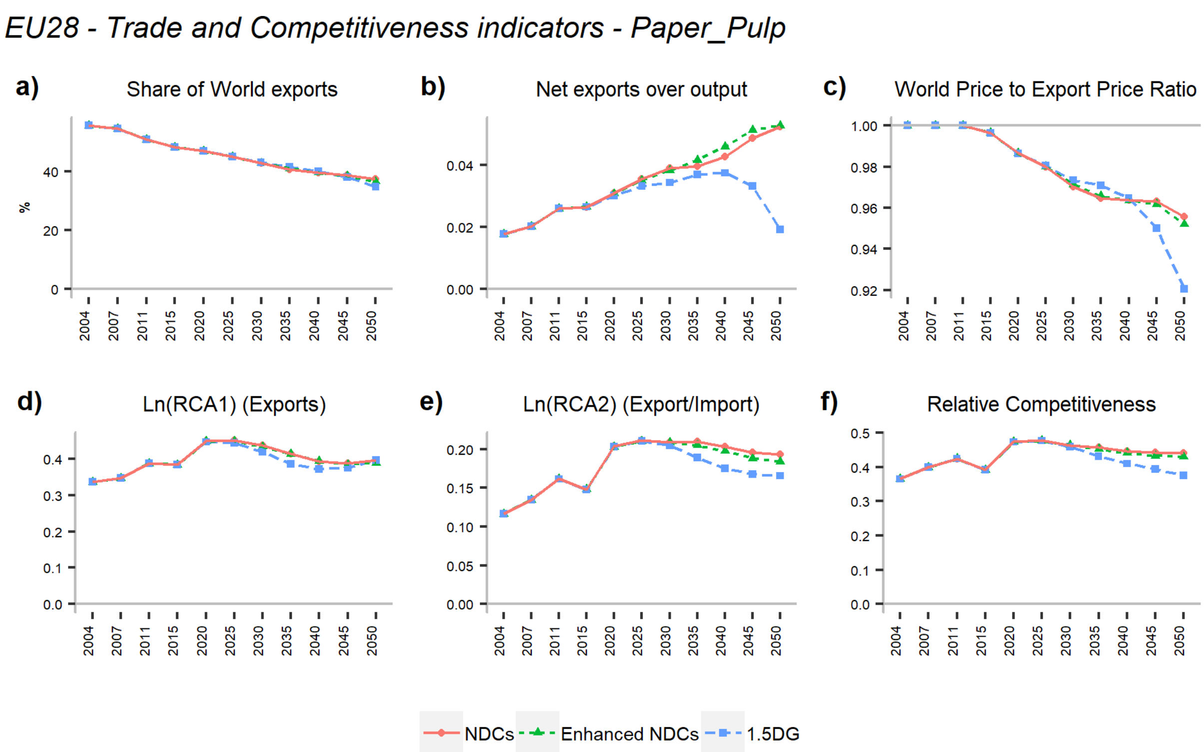

Figure 26: Trade and competitiveness indicators for the Paper & Pulp industry

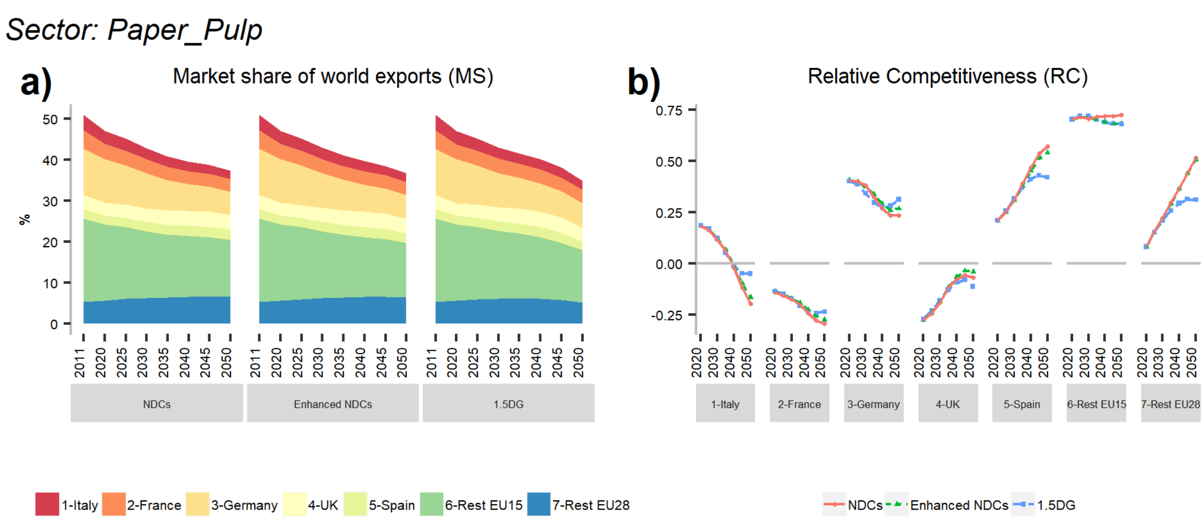

Figure 27: Paper & Pulp industry: Trade and competitiveness indicators by country

10.2 Chemicals

Export of Chemicals from the EU28 had a share of 51% in 2004 and around 45% in 2011. Differently from the previous case, the evolution associated to the three decarbonisation scenarios show different results after 2025 (see panel *a)* of Figure 28). The NDCs scenario has a relative stable trend (red line) while the Enhanced NDCs imply a steady reduction of the EU28's market share (green line). Conversely, in a more ambitious scenario in which the deployment of low carbon technologies is accelerated, the market share is above the NDCs scenario (blue line and square marker). Panel *b)* shows how net exports would be significantly reduced and become negative. However, after 2035 the industry could regain their competitiveness in the most ambitious scenario (1.5DG). Recalling Figure 11 showing that the production of Chemicals is very similar for all scenarios by 2030, the industry production remains stable and the region would become a net importer for a small amount around 2.5% of domestic production.

The evolution of net exports could be explained by the combination of measures selected for all scenarios that are basically applying energy efficiency measures which are then complemented with investments in more efficient capital at the beginning of the period followed by the intensified deployment of clean and renewable energies. In fact, in the 1.5 DG scenario where these trends have been imposed from the beginning at higher rates than the NDCs-based scenarios show better results in all trade and competitiveness indicators.

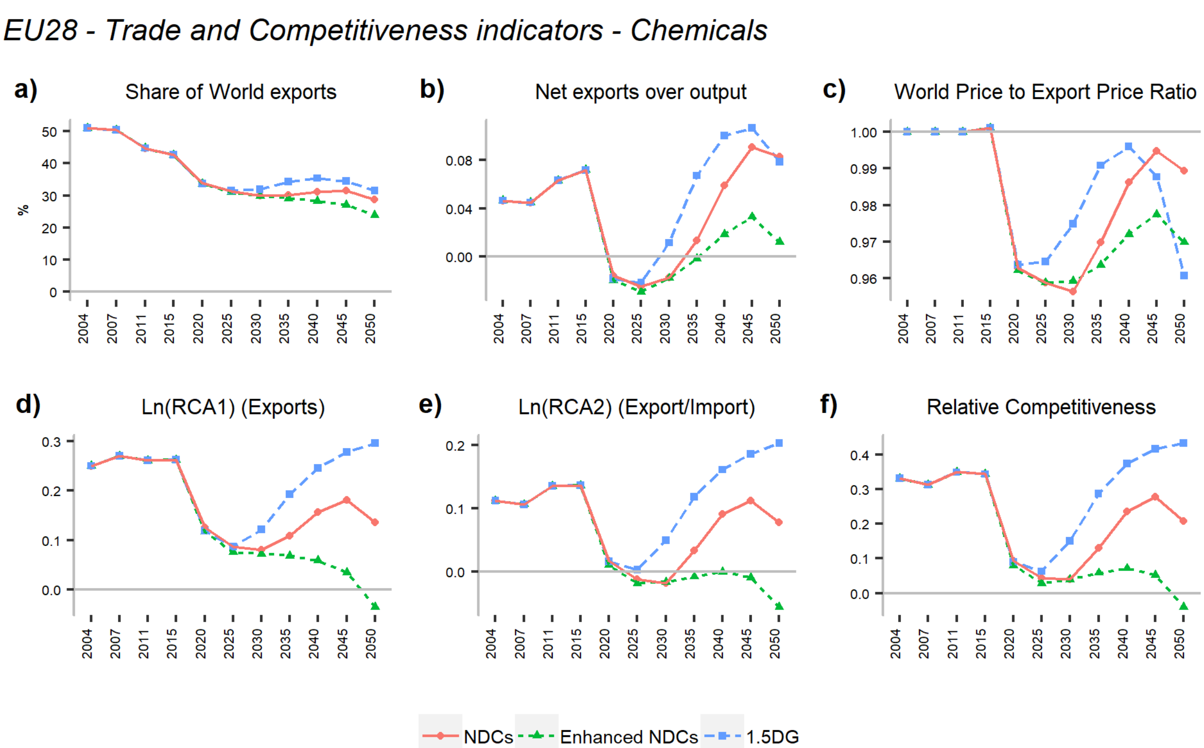

Figure 28: Trade and competitiveness indicators for the Chemicals industry

The distribution of the market share of world exports for EU countries is presented in panel *a)* of Figure 29. For 2011, Germany and France hold the highest shares (11% and 5.4% respectively) followed by UK, Italy, and Spain (3.7%, 3.2% and 2.1). While most EU countries would continue to decrease their market share, only the United Kingdom would maintain a relatively stable share through time. This is corroborated by the fact that the relative competitiveness of UK is the one that increases in all scenarios. While other countries such as France, Germany and the rest of EU15 report a positive *RC* index their trends are not always increasing. While there are countries like Italy and Spain having a comparative disadvantage in the Chemicals industry, their competitiveness may improve in the NDCs and 1.5DG scenarios, differently from the rest of EU28 where the trend for the *RC* indicator is always negative explaining also the low share of world exports.

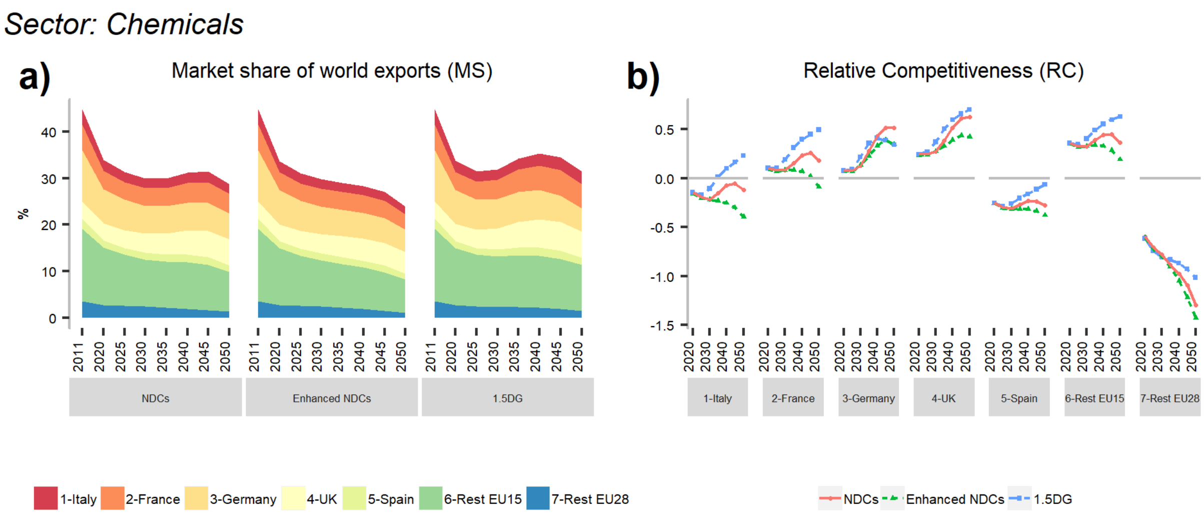

Figure 29: Chemicals: Trade and competitiveness indicators by country

10.3 Non-Metallic Minerals

This is the most carbon intensive industry in the European Union, which produced 52% of world exports in 2004, a share that decreased to 42% by 2011 and would continue with that trend in all simulated scenarios reaching around 25% by 2050 (see panel *a)* of Figure 30). Net exports would remain under 2% of EU's production through the entire interval as shown on panel *b)* with a sudden reduction of this ratio until 2020. Despite the declining export share, the trade and competitiveness indicators *RCA1* and *RC* in panels *d)* and *f)* respectively remain positive with higher values for the 1.5DG scenario showing better results until 2035 when all indicators show a decreasing trend, in part due to the higher efficiency achieved through technological advance embedded in the decarbonisation scenarios.

Looking at the country distribution of export shares presented in panel *a)* of Figure 31, Germany, Italy, France, and Spain provide 24% of world exports, even though their shares would decline in the future. As supported by the declining trends of relative competitiveness for most of EU regions, only Germany and the rest of EU28 would improve their competitiveness. The region that would be most affected by a loss of competitiveness would be the rest of EU15 with a reduction of their export share from 9% in 2011 to around 2% by 2050. Conversely, the rest of EU28 countries would increase their world market

share to from 7% to 9% with a steady rise in the relative competitiveness indicator during the same period.

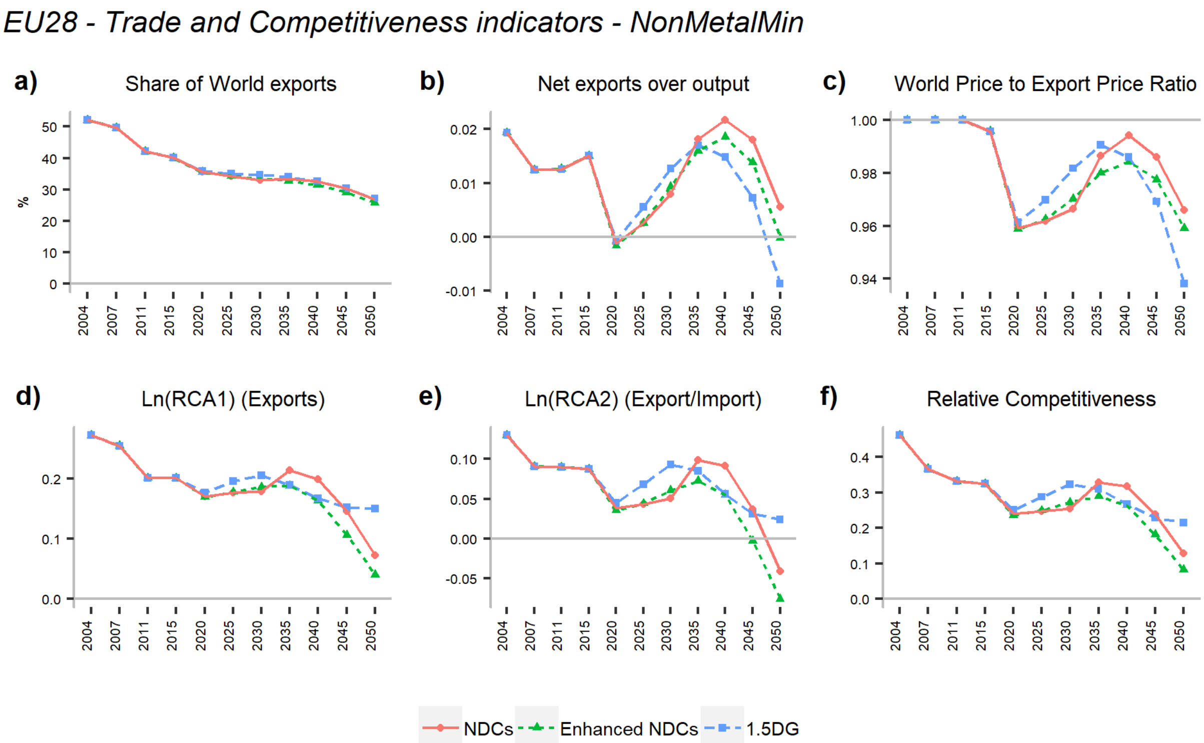

Figure 30: Trade and competitiveness indicators for the Non-Metallic Minerals industry

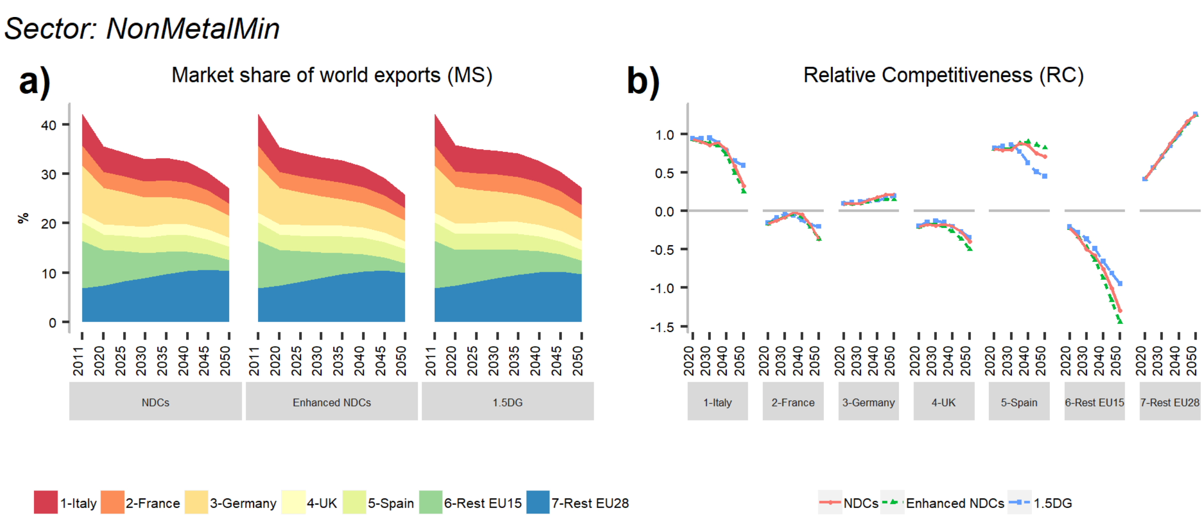

Figure 31: Non-Metallic Minerals: Trade and competitiveness indicators by country

10.4 Iron & Steel

The carbon intensity of the Iron & Steel industry considering only energy related CO2 emissions is the second in rank after Non-Metallic minerals. Its world market share in 2004 was 43% which declined to 38% by 2011 (see panel *a)* of Figure 32). While this share would decrease in the future, the trade and competitiveness indicators show a steady growth even in the context of the decarbonisation scenarios as shown in panels *b)* to *f)* of Figure 32. While both NDCs-based scenarios display a similar trend, it is only the 1.5 DG scenario that shows a more contained growth of exports and competitiveness.

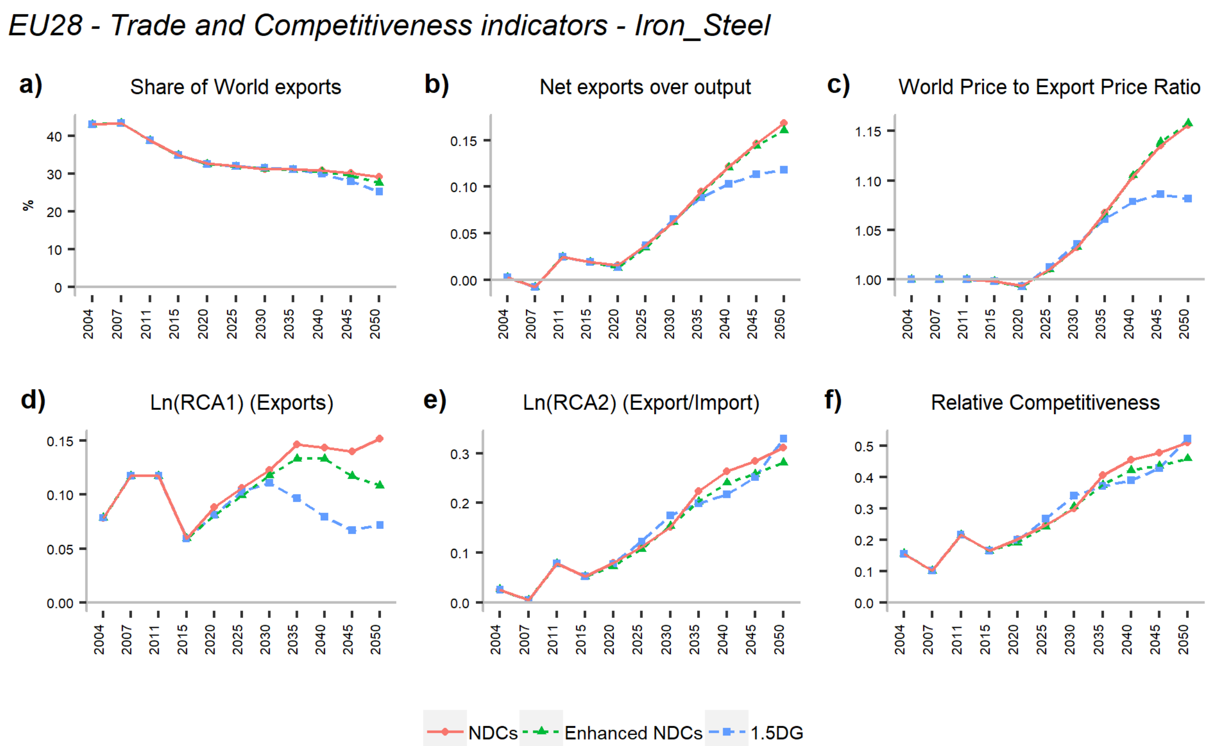

Figure 32: Trade and competitiveness indicators for the Iron & Steel industry

The main exporting countries in the EU28 in 2011 were Germany, France and Italy with 7.7%, 4.4%, and 3.9% respectively as shown in panel *a)* of Figure 33. In the decarbonisation scenarios these countries would improve their competitiveness along with the rest of EU15. Italy and France would even increase their market share in the future shown also with a steep raise in their *RC* indicator. While Spain and the western European countries from the rest of EU28 would have a modest result compared with eastern European countries. Only the United Kingdom displays a steep decline of relative competitiveness with a reduction between 20% to 30% of the market share. The countries/regions that show better results in the 1.5DG scenario are Spain and the rest of EU, while Italy, France, and Germany show better competitiveness trends in the NDCs-based scenarios.

Sector: Iron_Steel

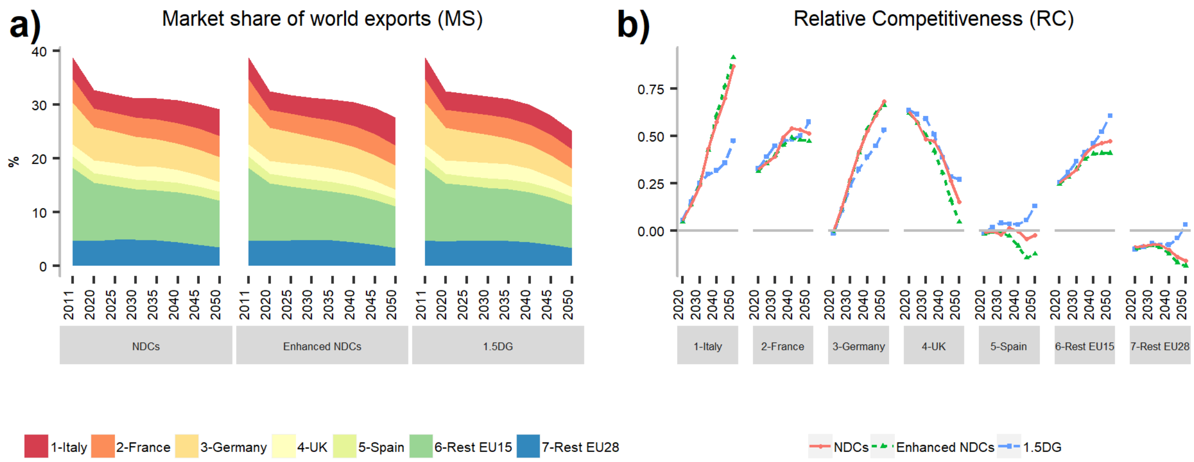

Figure 33: Iron & Steel: Trade and competitiveness indicators by country

10.5 Non-Ferrous Minerals

Even though the Non-Ferrous Minerals industry produced 25% of world exports, according to the trade and competitiveness indicators presented in Figure 34, the EU is a net importer (see panel *b*). The three indicators based on revealed comparative advantages show a negative value and despite presenting an increasing trend, they would remain negative for most of the time. This is also corroborated by the increasing trend of the ratio of World price to export price indexes (see panel *c*), showing that European export prices are increasing at a higher rate that world prices.

The Non-Ferrous mineral industries from almost all the European Union show a positive relative competitiveness index, with the exception of the United Kingdom who is a net importer with an increasing revealed comparative disadvantage. Within the decarbonisation scenarios only Italy would maintain or even rise the market share of exports while the rest of EU would reduce it by 2050. Finally, the NDCs-based scenarios show better results in terms of relative competitiveness than the more ambitious 1.5DG scenario. The only exception would be the rest of EU28 that does not see a relative competitiveness deteriorated during the simulation period.

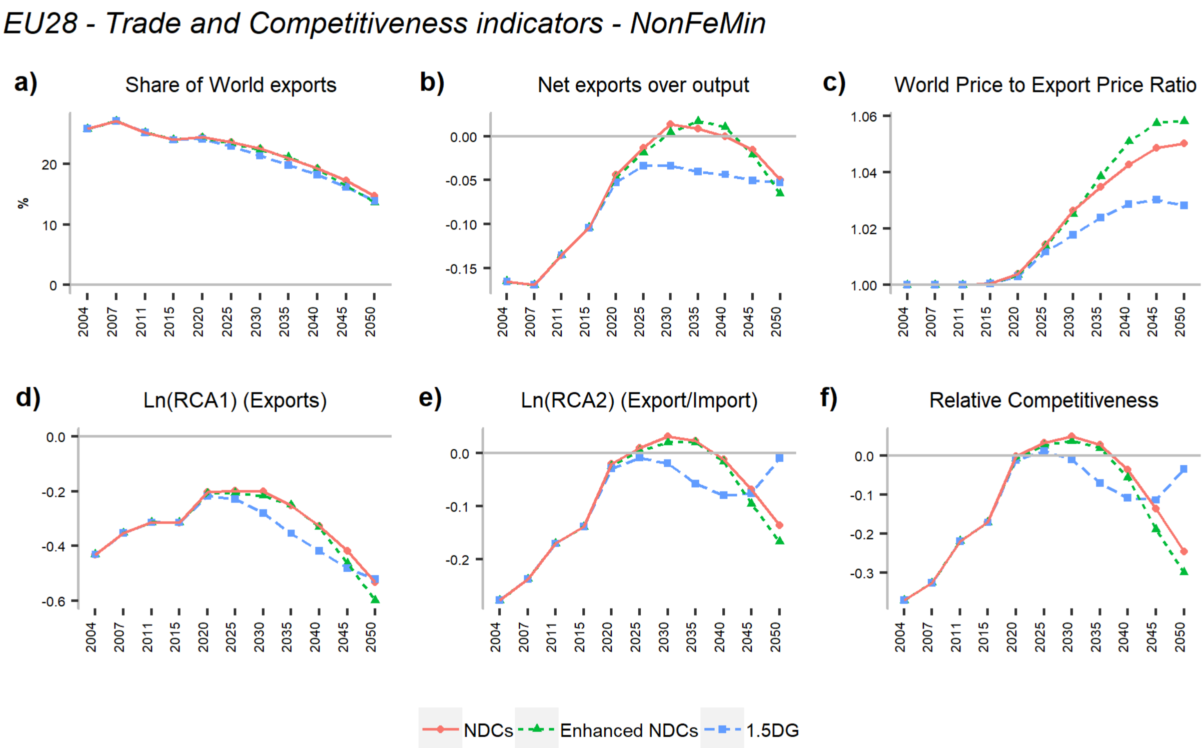

Figure 34: Trade and competitiveness indicators for the Non-Ferrous Minerals industry

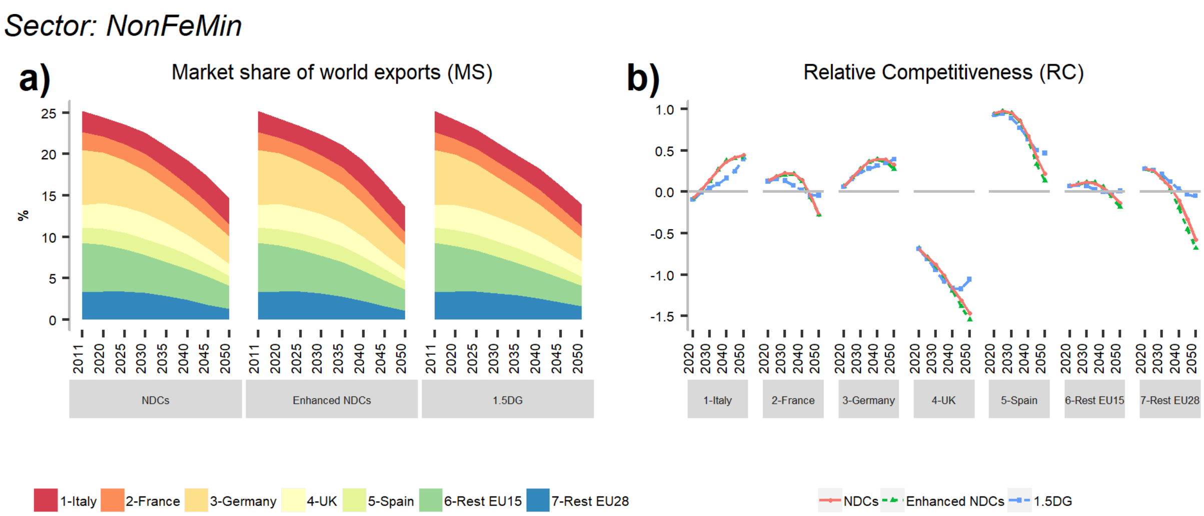

Figure 35: Non-Ferrous Minerals: Trade and competitiveness indicators by country

10.6 Vehicles

While this is not an EITE industry, it represents an important share of industrial production in the EU which is comparable to that of Chemicals production in 2011. The aggregated market share of industries related to vehicles for 2004 was 51% of world exports which slightly declined to 48% in 2011 as shown on panel *a)* of Figure 36. While this share would be 35% on average by 2050 in the decarbonisation scenarios, net exports represented 10% of EU's production in 2011 a share that would increase in the NDCs-based scenarios (see panel *b*). In addition, these industries would increase their competitiveness in the NDCs-based scenarios as shown on panels *d)* to *f)* of Figure 36.

EU28 - Trade and Competitiveness indicators - Vehicles

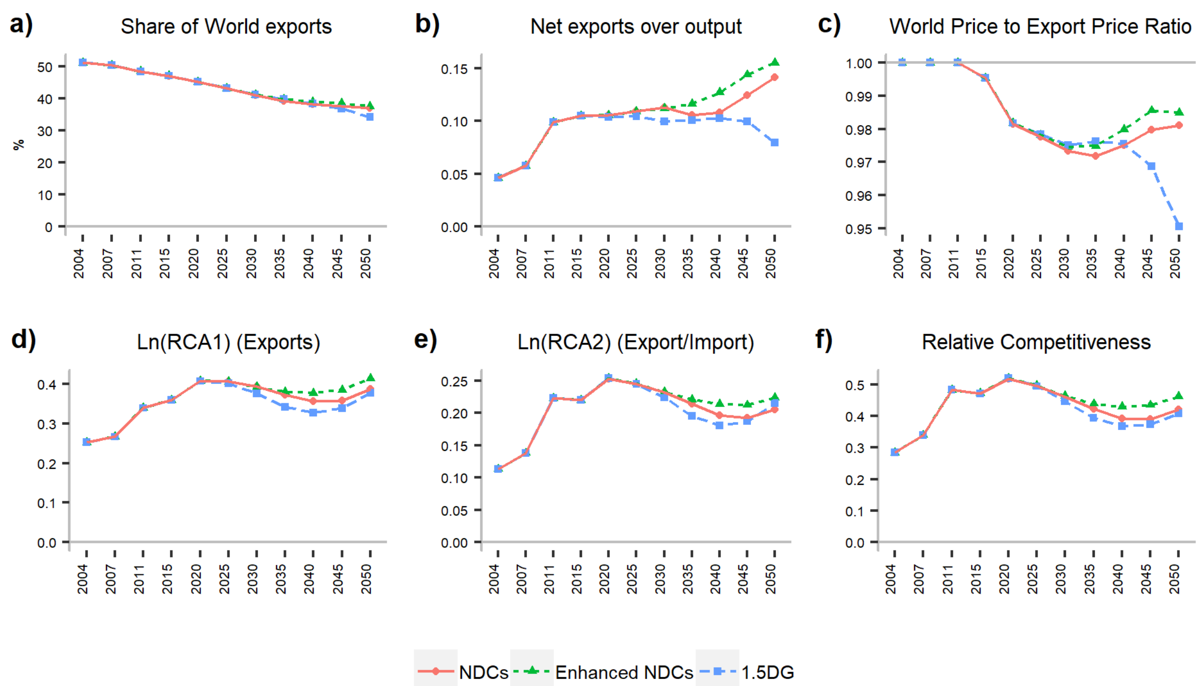

Figure 36: Trade and competitiveness indicators for the Vehicles industry

Sector: Vehicles

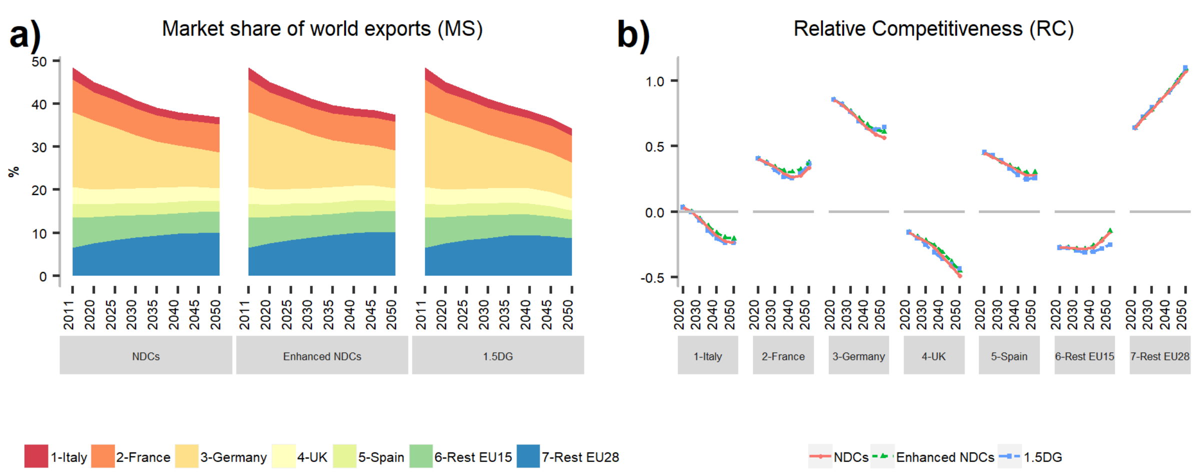

Figure 37: Vehicles: Trade and competitiveness indicators by country

The distribution of exports within the EU28 were concentrated in Germany (17.5%), followed by France (7.5%), UK (3.9%) and Spain (3.2%) in 2011. While there is a positive relative competitiveness in France, Germany, and Spain, the only country that would maintain the market share of exports would be France with the rest decreasing their world market share. A particular case is the region compounded by eastern European countries from the rest of EU28 that would increase their exports of vehicles as well as their relative competitiveness.

10.7 Machinery & Equipment

Production of Machinery & Equipment represented about 7% of EU's total output, even higher than Chemicals or Vehicles (see Figure 11). The market share of world exports corresponding to the EU28 was around 35% by 2004, and almost 32% in 2011. This share would continue to decrease in the future to less than 18% by 2050 (see panel *a)* of Figure 38). The trade and competitiveness indicators would decline in all three decarbonisation scenarios with better results in the Enhanced NDCs and NDCs scenarios.

The main EU exporters are Germany, Italy, France, and the United Kingdom with 10%, 3.5%, 2.8% and 2.3% respectively. However, the only countries showing a relative competitive advantage are Italy and Germany. From these two, only Italy would keep the world market share of exports stable after 2035 in the NDCs-based scenarios, while the German export share would drop to around 3% (see panel *a)* of Figure 39). In addition, France and the rest of EU15 would improve their relative competitiveness (panel *b)* of Figure 39) which would allow them to maintain a relatively stable share of world exports.

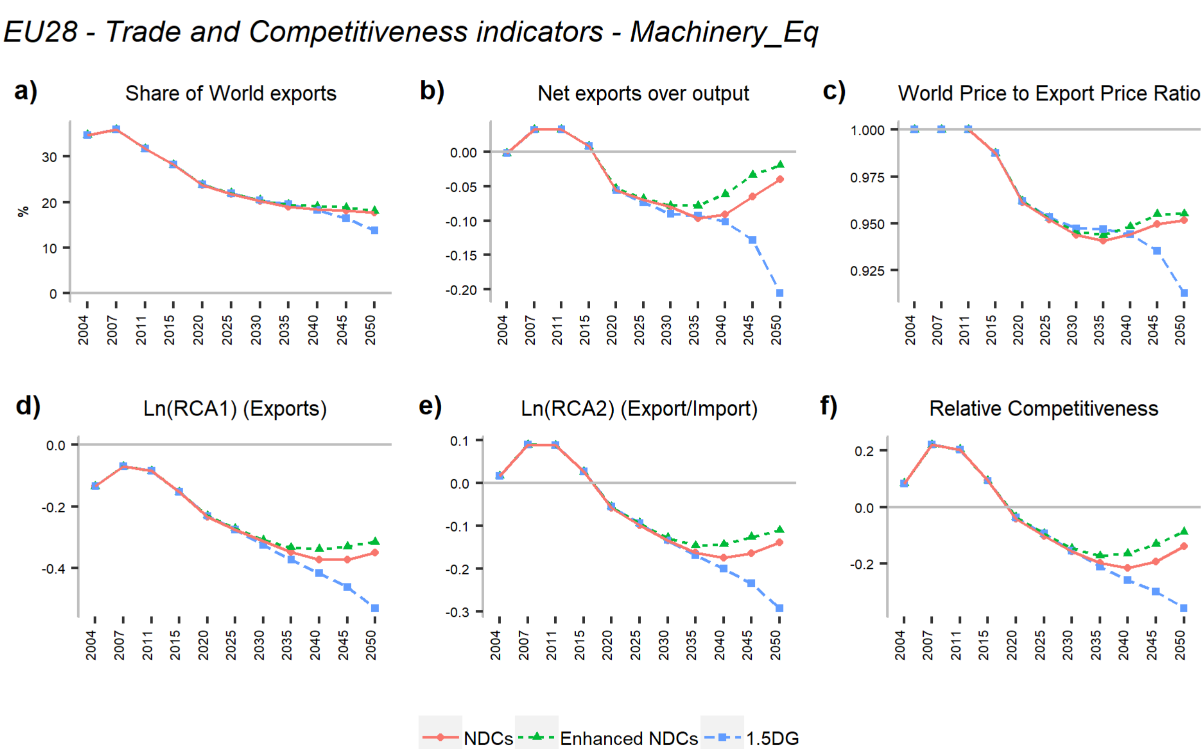

Figure 38: Trade and competitiveness indicators for the Machinery & Equipment industry

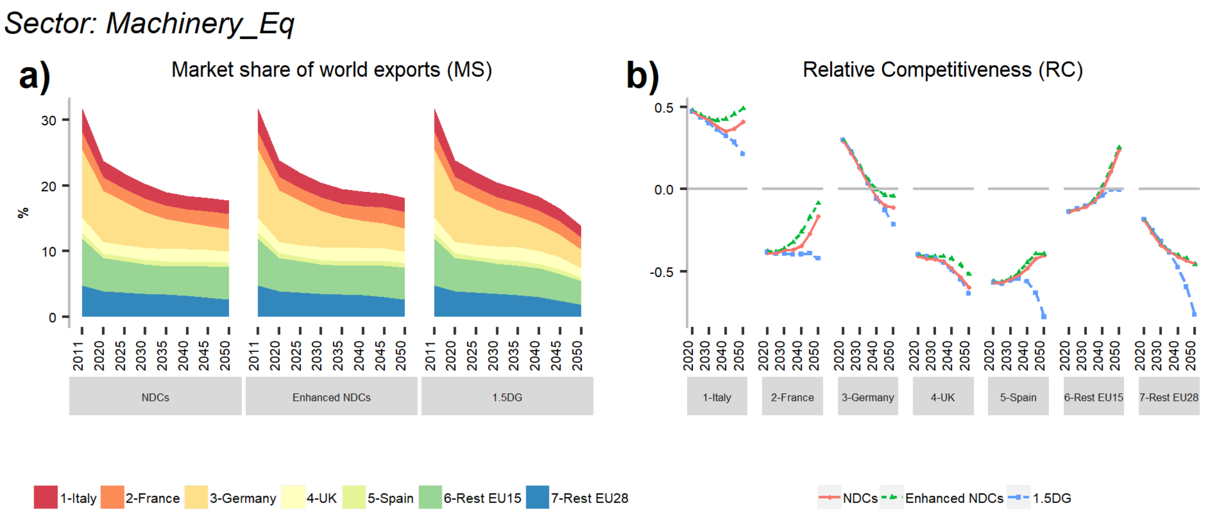

Figure 39: Machinery & Equipment: Trade and competitiveness indicators by country

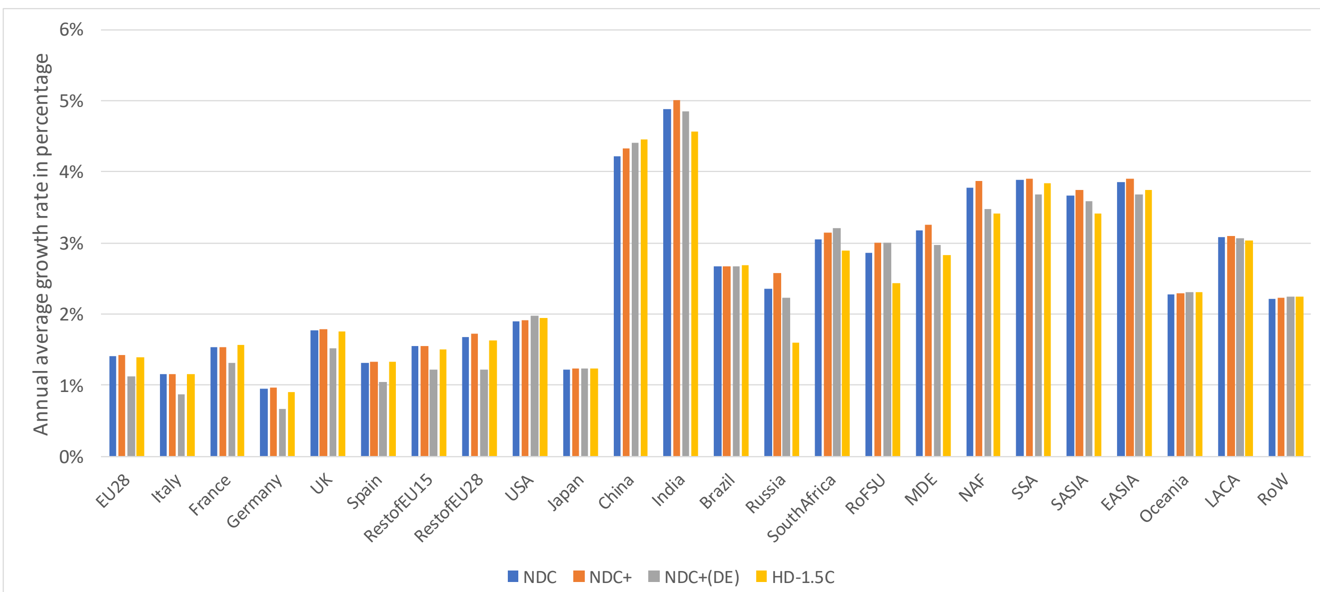

Figure 40: Annual average growth rate in the decarbonisation sceanrios by region

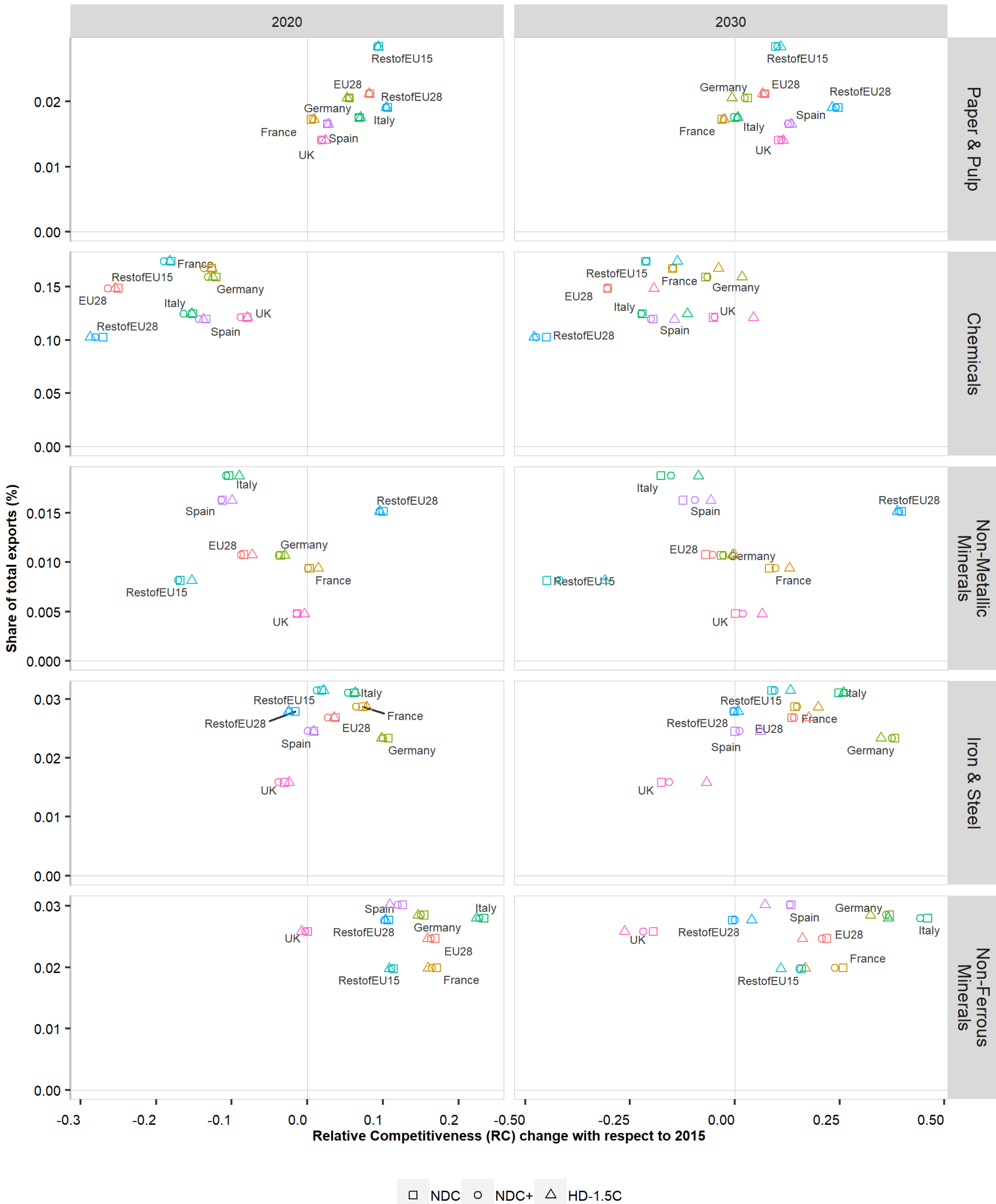

Figure 41: Change in relative competitiveness against national export share in 2020 and 2030 for EITE industries and by European country

11 Appendix B: The ICES Model description

ICES (Inter-temporal Computable Equilibrium System) is a top-down recursive-dynamic multi-region and multi-sector computable general equilibrium (CGE) model. Following is a detailed description of the supply and demand side of the model based on the GTAP, GTAP-E and ICES models (Hertel, 1997; Burniaux and Truong, 2002; Parrado and De Cian, 2014). Regional subscripts have been omitted for convenience in the following equations. For a complete detail of all the remaining equations, interested readers may refer to Hertel (1997).

Each industry is modeled as a cost-minimizing representative firm. Final output of sector j (Y_j) is a function of a technological index (A_j), aggregate value added-energy composite (VAE_j), other intermediate inputs (M_j), and α_j are distribution parameters. The elasticity of substitution for the top nest (σ_M) has been set equal to 0, therefore, representing a Leontieff specification.

$$Y_j = A_j\left[\alpha_{VAE,j}VAE_j^{\frac{\sigma_M-1}{\sigma_M}} + \alpha_{M,j}M_j^{\frac{\sigma_M-1}{\sigma_M}}\right]^{\frac{\sigma_M}{\sigma_M-1}} \tag{A1}$$

Aggregate value added-energy output, VAE_j, is produced with Z_i primary factors (i = land, labor, natural resources, and a capital-energy composite-KE), with an elasticity of substitution σ_{VAE} and a distribution parameter δ_{ij},.

$$VAE_j = \left[\sum_i \delta_{ij} Z_{ij}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}}\right]^{\frac{\sigma_{VAE}}{\sigma_{VAE}-1}} \tag{A2}$$

The capital-energy composite (KE) is produced by combining capital (K) and energy (E) as illustrated by equation A3 with a substitution elasticity σ_{KE}=0.25.

$$KE_j = \left[\alpha_{k,j}K_j^{\frac{\sigma_{KE}-1}{\sigma_{KE}}} + \alpha_{e,j}E_j^{\frac{\sigma_{KE}-1}{\sigma_{KE}}}\right]^{\frac{\sigma_{KE}}{\sigma_{KE}-1}} \tag{A3}$$

The Energy (E) nest compounds Electricity (EL) with Non-Electric energy (NEL) and an elasticity of substitution ($\sigma_{ELY}=0.16$):

$$E_j = \left[\alpha_{EL,j}EL_j^{\frac{\sigma_{ELY}-1}{\sigma_{ELY}}} + \alpha_{NEL,j}NEL_j^{\frac{\sigma_{ELY}-1}{\sigma_{ELY}}}\right]^{\frac{\sigma_{ELY}}{\sigma_{ELY}-1}} \tag{A4}$$

Non-electric energy (NEL) is composed of Coal and Non-Coal energy, assuming an elasticity of substitution of $\sigma_{COAL}=0.07$.

$$NEL_j = \left[\alpha_{COAL,j} COAL_j^{\frac{\sigma_{COAL}-1}{\sigma_{COAL}}} + \alpha_{NCOAL,j} NCOAL_j^{\frac{\sigma_{COAL}-1}{\sigma_{COAL}}} \right]^{\frac{\sigma_{COAL}}{\sigma_{COAL}-1}} \quad \text{(A5)}$$

Liquid fossil fuels (*F*) are combined in a composite (*NCOAL*) also following a CES production function with the elasticity of substitution ($\sigma_{FF}=0.25$):

$$NCOAL_j = \left[\sum_i \beta_{i,j} F_{i,j}^{\frac{\sigma_{FF}-1}{\sigma_{FF}}} \right]^{\frac{\sigma_{FF}}{\sigma_{FF}-1}} \qquad i = \text{oil, gas, oil products} \quad \text{(A6)}$$

The electricity bundle is obtained by combining the Transmission and Distribution services (TnD) with Electricity Generation (EG) with and substitution elasticity $\sigma_{EL}=0$.

$$EL_j = \left[\alpha_{TnD} TnD_j^{\frac{\sigma_{EL}-1}{\sigma_{EL}}} + \alpha_{EG} EG_j^{\frac{\sigma_{EL}-1}{\sigma_{EL}}} \right]^{\frac{\sigma_{EL}}{\sigma_{EL}-1}} \quad \text{(A7)}$$

The electricity generation is represented by three main power generation technologies: Nuclear (Ely_N), a bundle for renewables (Ely_R - including Hydro, Solar, and Wind), a bundle for fossil fuels (Ely_O) and a bundle for fossil fuels with carbon capture and sequestration (Ely_CCS) with an elasticity of substitution σ_{EG}.

$$EG_j = \left[\alpha_{Ely\_N} Ely\_N_j^{\frac{\sigma_{EG}-1}{\sigma_{EG}}} + \alpha_{Ely\_R} Ely\_R_j^{\frac{\sigma_{EG}-1}{\sigma_{EG}}} + \alpha_{Ely\_O} Ely\_O_j^{\frac{\sigma_{EG}-1}{\sigma_{EG}}} + \alpha_{Ely\_CCS} Ely\_CCS_j^{\frac{\sigma_{EG}-1}{\sigma_{EG}}} \right]^{\frac{\sigma_{EG}}{\sigma_{EG}-1}}$$

(A8)

The “Armington” assumption makes domestic (*DOM*) and foreign (*IMP*) commodities imperfect substitutes in accounting for product heterogeneity.

$$M_i = \left[\alpha_{dom,i} DOM_i^{\frac{\sigma_{dom}-1}{\sigma_{dom}}} + \alpha_{imp,i} IMP_i^{\frac{\sigma_{dom}-1}{\sigma_{dom}}} \right]^{\frac{\sigma_{dom}}{\sigma_{dom}-1}} \quad \text{(A9)}$$

Imported commodities are a composite of commodity *i* from all source regions (*s*).

$$IMP_i = \left[\sum_s o_{i,s} Y_{i,s}^{\frac{\sigma_{imp}-1}{\sigma_{imp}}} \right]^{\frac{\sigma_{imp}}{\sigma_{imp}-1}} \quad \text{(A10)}$$

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, land, labor, and capital). Capital and labor are perfectly mobile domestically but immobile internationally. Land and natural resources, in contrast, are industry-specific. Income is used to finance three classes of expenditure: aggregate household consumption, public consumption and savings. The expenditure shares are generally fixed, which amounts to saying that the top-level utility function has a Cobb-Douglas specification. The top-level demand system is described by a Cobb-Douglas utility function where the aggregate utility involves the per-capita utility from private and government consumption, and real savings.

$$U = CU_P^{\omega_P} U_G^{\omega_G} U_S^{\omega_S} \quad \text{(A11)}$$

where U is the per-capita aggregate utility while U_P, U_G, and U_S are, respectively, the per-capita utility from private and government consumption, and real savings; whilst ω_i represent their distributional parameters.

Real savings is a single commodity deflated by the saving price. Government preferences have the same functional form of the top-level utility function while the demand system of private consumption is split according to a Constant Difference in Elasticities (CDE) functional form. The CDE demand system is characterized by an indirect utility function of the form:

$$1 = \sum_i B_i U^{\gamma_i R_i} \left(\frac{P_i}{X} \right)^{\gamma_i} \quad \text{(A12)}$$

with P_i, being price of commodity i, X the household expenditure, while B_i, γ_i, and R_i are positive parameters. This non-homothetic function enables accounting for possible differences in income elasticities for the various consumption goods. The regional household maximizes the aggregate utility under a budget constraint depending on per capita income, defined as the service value of national primary factors (natural resources, land, labor and capital). The budget constraint takes the following form:

$$E_P(P_P, U_P) + E_P(P_G, U_G) + P_S U_S = X \quad \text{(A13)}$$

where E_P, E_G are per capita expenditure functions; P_P, P_G, P_S are price vectors, and X is per capita income, defined as the service value of national primary factors (natural resources, land, labor and capital).

Growth is driven by changes in primary resources (capital, labor, land and natural resources). Dynamics are endogenous for capital and exogenous for other primary factors. Capital accumulation is the outcome of the interaction of: i) investment allocation between regions and ii) debt accumulation. Savings are pooled by a world bank and allocated as regional investments according to:

$$\frac{I_r}{Y_r} = \phi_r \exp[\rho_r (r_r - r_w)] \quad \text{(A14)}$$

where: I_r is regional annual investment, Y_r is regional income, r_i is regional and world returns on capital, ϕ_r is a given parameter that represents the average propensity to save and ρ_r is a flexibility parameter related to investment supply sensitivity to return differentials. The rationale of equation (A12), follows the ABARE GTEM model (Pant, 2002). Capital stock accumulates over time in a standard relationship with a constant depreciation:

$$K_r^{t+1} = I_r^t + (1-\delta) \cdot K_r^t \quad \text{(A15)}$$

There is no equalization of regional investments and savings from equation (A14), so any excess of savings over investments equals the regional trade balance (*TB*). Investment is internationally mobile and allocated across countries to equalize expected rates of return to capital in the long-run. Savings and investments are equalized at the world level, but each region could have an imbalance between disposable savings and investment demand. This imbalance is closed by a surplus/deficit in foreign transactions (considered as the sum of trade surpluses/deficits and the net inflows of international transfers).

The stock of debt evolves by considering the trade balance as follows:

$$D_r^{t+1} = TB_r^t + D_r^t \quad \text{(A16)}$$

Finally, foreign debt is serviced every period on the basis of the world interest rate r_w.

12 Appendix C: ICES Regional definition

Table 5: ICES regional definition

Region	Description
Italy	Italy
France	France
Germany	Germany
UK	United Kingdom
Spain	Spain
Rest of EU15	Austria, Belgium, Denmark, Finland, Greece, Ireland, Luxemburg, Netherlands, Portugal, Sweden
Rest of EU	Cypruss, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, Slovenia, Bulgary, Croatia, Romania
United States of America	United States of America
Japan	Japan
China	China, Hong Kong
India	India
Brazil	Brazil
Russia	Russia
South Africa	South Africa
Rest of Former Soviet Union	Belarus, Ukraine, Rest of Eastern Europe, Kazakhstan, Kyrgyztan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia
Middle East	Bahrain, Iran, Israel, Jordania, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Rest of Western Asia
North Africa	Egypt, Morocco, Tunisia, Rest of North Africa
Sub-Saharian Africa	Benis, Burkina Faso, Cameroon, Côte d'Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Rest of Western, Central, South Africa, Ethiopia, Kenia, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, Namibia, Rest of South African Customs Union
Southern Asia	Bangladesh, Nepal, Pakistan Sri Lanka, Rest of South Asia
Eastern Asia	Korea, Mongolia, Taiwan, Rest of East Asia, Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, Vietnam, Rest of South East Asia
Oceania	Australia, New zealand
Latin and Central America	Mexico, Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America, Dominican Republic, Jamaica, Puerto Rico, Trinidad & Tobago, Rest of Caribbean, Rest of the World
Rest of the World	Canada, Norway, Switzerland, Rest of North America, Rest of Europe

13 Annex D. Production structure and technological progress in MEWA model

Production Structure

The production function in MEWA model reflects the substitution possibilities between different inputs as well as externalities generated by R&D investments. The firms maximise the expected discounted sum of profits defined as:

$$\Pi_0^i = \sum_{t=0}^{+\infty} \Lambda_t \pi_t^i$$

Where $\Lambda_{t+1} = \beta \frac{\lambda_{t+1}^C}{\lambda_t^C} \Lambda_t$ is the stochastic discount factor, mirroring the preferences of households that own the firms, as λ_t^C is a Lagrange multiplier associated with households' budget constraint. Current cash flow is denoted by π_t^i and calculated in the following manner:

$$\pi^i = \left(1 - {TX_{PROD_R}}^i\right) * {P_H}^i * {Y_H}^i - W^i * L^i - I\_COST^i - {COST_{INT}}^i - {RND_{VAL}}^i - CO2^i * \varphi^{CO2},$$

where $\left(1 - {TX_{PROD_R}}^i\right) * {P_H}^i * {Y_H}^i$ is the value of production adjusted for taxes on production and $W^i * L^i$ is labour cost (wage multiplied by labour input). I_COST^i is investment cost defined as:

$$I\_COST_t^i = {P_{INV}}_t * I_t^i + \frac{\varphi^{INV}}{2} * \left(\frac{I_t^i}{K_{t-1}^i} - \delta^{K,i}\right)^2,$$

where ${P_{INV}}_t * I_t^i$ is the price of actual investment while the term $\frac{\varphi^{INV}}{2} * \left(\frac{I_t^i}{K_{t-1}^i} - \delta^{K,i}\right)^2$ reflects investment adjustment costs. ${COST_{INT}}^i$ is the cost of the intermediate inputs, ${RND_{VAL}}^i$ is the value of R&D expenditures and $CO2^i * \varphi^{CO2}$ is the cost of the GHG emissions. A firm can decrease emission intensity of its production through in-house R&D investments.

Technological progress

The MEWA model incorporates technological progress through the endogenous, directed technological change that may improve the efficiency of production input utilisation (in this report: emission efficiency and labour productivity) on the sectoral level. The technological progress relies on improving the specific features of the capital that is employed in a given sector, i.e. capital goods have additional, embedded attributes – emission and labour efficiency ($X_t^{i,s}$, where i indicates sector and $s \in \{EM, LAB\}$ indicates the type of technological change). The evolution of this feature is governed by the following equation:

$$K_t^i X_t^{i,s} = (1 - \delta^s \eta^{-1}) K_{t-1}^i X_{t-1}^{i,s} + \left(\frac{I_t^i}{K_{t-1}^i}\right)^\eta K_{t-1}^i A_{t-1}^s Z_t^{i,s}$$

In this equation K_t^i denotes capital deployed in a sector i, $Z_t^{i,s}$ measures the R&D activity s in sector j, while A_{t-1}^s denotes the technological frontier at the start of period t for the attribute s. Firms, at the expense of their current profits, can increase the level of $Z_t^{i,s}$ to make their investments more efficient. Increase in $Z_t^{i,s}$ requires additional spending:

$$Z\_VAL_t^{i,s} = {Z_t^{i,s}}^{\alpha_s} \phi^s.$$

When firms invest in improving the efficiency of their own capital, they also shift the economy-wide technological frontier for the attribute s. Thus, the model captures positive externalities (knowledge spillovers) stemming from investing in the attribute $Z_t^{i,s}$. The movement of the technological frontier is given by:

$$A_t^s = (1 - \delta_A^s) A_{t-1}^s + \delta_A^s * (\omega_s {Z_t^s}^{\psi_s} + (1 - \omega_s) I\_PUB\_RND_t^{s\,\psi_s})^{1/\psi_s},$$

where A_t^s is the current technology frontier for attribute s and $Z_t^s = \frac{\sum_{j \epsilon S} I_t^s Z_t^{i,s}}{\sum_{j \epsilon S} I_t^s}$ is weighted total R&D investment for the attribute $Z_t^{i,s}$ over all sectors of the economy. The improvement of the technology frontier A_t^s may also be driven by public R&D spending for the attribute s ($I\_PUB\_RND_t^s$). Similarly to the private investment, however, this additional public expenditure should be somehow financed, either through higher taxation or reduced government spending on other goods and services or transfers.