D3.2 – CASE STUDY ON CARBON LEAKAGE AND COMPETITIVENESS

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About this report

The EU is planning to become a low-carbon society and, in order to do so, is imposing ambitious targets for its emissions until 2050. Therefore, it is important to predict what kind of impacts these actions will bring to different sectors and the entire economy. This work touches the economic aspects of pursuing such targets, especially for industries that have a higher risk of carbon leakage, presenting results for a large number of policy measures in the EU-28, combined with different emission targets outside of it. Finally, it suggests which actions can positively impact the energy intensive sectors and promote their competitiveness under ambitious environmental targets.

REEEM partners

About REEEM

REEEM aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. This project is developed to address four main objectives: (1) to develop an integrated assessment framework (2) to define pathways towards a low-carbon society and assess their potential implications (3) to bridge the science-policy gap through a clear communication using decision support tools and (4) to ensure transparency in the process.

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Contents

About this report ... 2

Authors ... 2

List of Figures ... 5

Index of Tables ... 6

Abbreviations ... 7

1. Introduction ... 8

1.1. Carbon leakage ... 9

1.1.1. Relevant literature ... 10

2. Current Policy Framework ... 13

2.1. Climate policies ... 13

2.2. The actual state of policies in the EU ... 14

2.2.1. Policies to address carbon leakage ... 15

3. Methodology ... 17

3.1. Modelling Framework ... 17

3.2. Model's limitations ... 17

3.3. Stakeholders' integration ... 18

3.4. Modelling assumptions ... 18

3.5. Scenario definition ... 19

3.5.1. World and European states ... 20

3.5.2. Policy measures ... 21

3.5.3. Scenario construction ... 23

3.5.4. Central pathways ... 24

4. Modeling results ... 25

4.1. Relationship between emissions reduction and GDP growth ... 25

4.2. CO_2 production outside of the EU-28 ... 26

4.3. Impacts within EU-28 ... 28

4.3.1. Gross value added – European policies ... 29

4.3.2. Gross value added – Emission targets outside of the EU-28 ... 30

4.4. Electrification ... 31
4.5. Effects of the free allocation of allowances ... 33
5. Conclusion ... 35
6. Bibliography ... 37
Appendix ... 40
A.1 Carbon leakage ... 40
A.2 Modeling framework ... 41
A.3 Assumptions ... 45
Regional Push ... 48
A.4. Free allocation of allowances - implementation ... 49

List of Figures

Figure 1: Categorization of policies 13
Figure 2: GDP growth versus CO_2 emissions reduction for all scenarios from this study in EU-28......... 25
Figure 3: Relationship between GDP growth and CO2 emissions reduction with distinction of EU policies and world ambition 26
Figure 4: Difference in the CO2 emissions between the E1(BaU) and other emission targets for EU-28 27
Figure 5: CO_2 emissions in regions outside of the EU-28 in the year 2050 28
Figure 6: CO2 emissions per sector in 2050 in the EU-28 29
Figure 7: Gross Value Added in 2050 in the EU-28 for different sectors and EU ambition levels and policies 30
Figure 8: Gross Value Added in 2050 in the EU-28 for different sectors and world ambition levels...... 31
Figure 9: GDP of EU-28 in %-difference to 2011 for different substitution elasticities (EoS in REEEM Pathway = 0.1) 32
Figure 10: Gross Value Added in 2050 in EU-28 for different sectors, scenarios and elasticities of substitution (Cluster Union (EoS = 0.1) = 100%) 32
Figure 11: CES structure in NEWAGE for the production sectors 41
Figure 12: CES structure in NEWAGE for electricity production 41
Figure 13: Regional disaggregation in NEWAGE. Each region in the model has its own color in the map 44
Figure 14: Historical and projected share of free allowances for the oil refining sector 50
Figure 15: Historical and projected share of free allowances for the paper, pulp and print sector 50
Figure 16: Historical and projected share of free allowances for the iron and steel sector 51
Figure 17: Historical and projected share of free allowances for the non-ferrous metals sector 51
Figure 18: Historical and projected share of free allowances for the non-metallic minerals sector 52
Figure 19: Historical and projected share of free allowances for the chemistry sector 52

Index of Tables

Table 1: Scenarios - World states 20
Table 2: Scenarios - European states 20
Table 3: Scenarios constructed 23
Table 4: Emission reduction (Mt CO_2) in 2050 relative to 2011 27
Table 5: Results for Free Allowance scenario against E1W1(BAU) and E1W2 in the EU-28 33
Table 6: Results for REEEM Pathway with Free allowances vs without free allowances 34
Table 7: Carbon leakage definitions 40
Table 8: List of production sectors in NEWAGE 42
Table 9: Technology portfolio available at the electricity sector of NEWAGE 43
Table 10: Substitution elasticities in NEWAGE for consumption 45
Table 11: Substitution elasticities in NEWAGE for industry production 45
Table 12: Substitution elasticities in NEWAGE for electricity production 46
Table 13: Substitution elasticities in NEWAGE for trade 46
Table 14: Emission reduction targets for the REEEM pathway – in the EU 47
Table 15: Emission targets for regions outside of the EU-28 pursuing emission cuts higher than the current policies for the Regional Push World state 48

Abbreviations

AEEI	Autonomous Energy Efficiency Index
BaU	Business-as-Usual
CES	Constant Elasticity of Substitution
CGE	Computable General Equilibrium
ETP	Energy Technology Perspectives
ETS	Emissions Trading System
ESD	Effort Sharing Decision
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GVA	Gross Value Added
NEWAGE	National European Worldwide Applied General Equilibrium

1. Introduction

With the Paris Agreement, for the very first time a consent to put effort on climate change mitigation on a global level was expressed and captured in a legally binding document [1]. Climate change mitigation, however, can be achieved through different policy measures and, consequently, its economic consequences may differ considerably. Therefore, the expected effects of different climate policies on the economy need to be estimated and taken into account for political decisions. The goal of this report is to assist policy makers in this process. In order to do so, different policy interventions were analyzed with respect to their economic impacts in general and, more specifically, with regard to the risk of carbon leakage and their effects on competitiveness of the European industry sectors.

The analysis was conducted with a Computable General Equilibrium (CGE) model and, in order to gain conclusions about different policy options, different scenarios were constructed and calculated. The modeling results improve the understanding of interdependencies within the European economy and between Europe and the rest of the world. "Losers" and "winners" of different decarbonization policies can thus be identified, implications for different industry sectors can be seen and complementing policies can be suggested in order to prevent negative side effects.

Besides, stakeholders were integrated in the research process. This approach further improves the insights and the outcomes of the scientific research, since a more holistic picture can be drawn. The integration of stakeholders pursued three goals. First, stakeholders were to be informed regarding low carbon policy implications in order to improve their knowledge on this issue. Second, stakeholders' views on the modeling exercise were to be obtained in order to improve the scenarios and assumptions and, hence, the modeling in general. Last, policy implications were to be discussed in order to understand their precise effects on different industries and in the European economy.

This work was developed in the framework of the REEEM[1] project, which main goal is to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. Therefore, more than being a standalone report, the results obtained in this analysis will be utilized as input by other project partners in order to create an integrated assessment framework, where a number of different models are utilized together, allowing us to minimize each model's limitation and produce a more complete analysis of this complex issue.

The report is structured as follows: After giving a short overview of current literature, the concept of carbon leakage is introduced and the current policy framework is summarized. Subsequently, the methodology is explained. This includes a description of the CGE model utilized in this analysis, NEWAGE, an outline of the main assumptions, a description of the scenarios and how the stakeholders'

[1] For more information about the REEEM project, access reeem.org

feedback was integrated to this work. Next, main results for selected scenarios are presented and, lastly, major conclusions are drawn, as well as policy orientations.

1.1. Carbon leakage

Carbon leakage is in general defined as the leaking or transfer of emissions from one country to another caused by the carbon policy differences. Specifically, and according to the definition of the European Commission, it "refers to the situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints" [2]. In effect this states that climate policies cause an increase in energy costs, notably in increased production costs. This definition, however, can be extended, since not only production costs but also return on investment and global fossil fuel prices are eventually influenced by climate policies[2]. In consequence, carbon leakage can range from the transfer of production to transfer of investment or even a general increase in fossil fuels usage in other countries. While the transfer of production is a relatively flexible operational issue, the transfer of investment results in long-term changes of production patterns and, consequently, might cause a long-term increase in emissions. All those different types of carbon leakage, however, provoke the same effect, which is an increase of emissions in the rest of the world due to stricter climate policies within one country or region. The initial aim of reducing emissions is thus ineffectively achieved since the decrease is partly outweighed.

Besides, carbon leakage might be observed not only between different jurisdictions (countries, regions) but also between sectors or even business entities that face asymmetric carbon policies. This occurrence is denominated as internal carbon leakage. For example, an Emissions Trading System (ETS) might cause increased emissions from installations not covered by the ETS.

While carbon policy asymmetries can directly cause carbon leakage, there are at least four other channels through which carbon leakage can be stimulated:

- **Competitiveness** – carbon policies increase the costs of production in the region and domestic products are replaced by foreign ones. This results in operational leakage in the short-term and investment leakage in the long-term.
- **Technology spillovers** – higher production costs may stimulate the development of new technologies which can result in positive effects on competitiveness and carbon emissions.
- **Income effect** – carbon policies may have an impact on the income of consumers change the demand for different products which can result in both positive and negative leakages.

[2] More specific definitions of carbon leakage vary depending on their focus and scope and are listed in Appendix A.1 Carbon leakage.

- **Energy market** – carbon policies in some countries decrease the global prices for fossil fuels and increase their attractiveness in countries without corresponding carbon policies

Those channels are affected simultaneously, and the role of each of the channels depends very much on the design of carbon policies under consideration as well as on further circumstances. For instance, the energy market channel might cause carbon leakage if the decrease of global fossil fuel prices is significant enough to increase fossil fuel use in the jurisdictions that are not covered by the carbon policy. If this is not the case, however, carbon leakage might still occur due to increased production levels in the new competitive situation. Finally, it is possible that technology spillovers or income effects either offset or enhance carbon leakage effects.

While carbon leakage is a drawback for emission reduction efforts it is also perceived as a major threat to the competitiveness of certain energy intensive industries. Competitiveness is the ability to offer better or cheaper products or services than domestic and international competitors. At a sectoral level it reflects the attractiveness of a country for a particular industry. In carbon leakage context, it is important to distinguish the difference between the competitiveness at the company and at the sectoral levels. For a company, relocation of investment might be the factor that increases its competitiveness compared to other companies that do not make similar actions. However, at the sectoral level this is a loss of competitiveness since the ability to compete of domestic industry is lower compared to foreign ones [3].

Sectoral competitiveness can be measured in terms of net exports and investment flows [4]. Every policy leading to an increase in production costs reduces the competitiveness of a firm or an industry. On the other hand, competitiveness can also be positively influenced by environmentally friendly innovations induced by climate policy. Whether competitiveness is negatively affected by climate policies can thus not be easily answered.

Competitiveness is considered as an important indicator to look at since it is directly related to the business' performance. Thus, not only the efficiency of climate policies is indicated, but also the impact on the economic growth and such sensitive indicators as unemployment (production shifting to different jurisdictions also means the loss of domestic jobs), taxes, etc. This channel therefore deserves especial political attention seeking to ensure that carbon policies are not harmful to the economy.

This report investigates, therefore, in which degree carbon leakage and competitiveness are connected and what can be done, policy-wise, to minimize the negative economic effects of GHG emission reductions.

1.1.1. Relevant literature

The issues related to carbon leakage, changes in competitiveness and other possible consequences of carbon policies are widely discussed in scientific literature. The existing research can be broadly classified to ex-post empirical research which examines the implications of carbon policies and ex-ante analyses which try to predict possible impacts of policies to be implemented in the future. Despite different focus, both approaches can provide relevant insights for policymaking.

The loss of competitiveness and carbon leakage due to carbon policy asymmetries can be easily explained theoretically, but there is a lack of empirical evidence on the significant occurrence of those effects in the past. Ex-post empirical literature reviews show that even if there are statistically significant relationships, they result in very small impacts of environmental policies (emission trading, carbon taxation, etc.) on competitiveness indicators [4] [5] and, consequently, on carbon leakage. The simulations performed by Sato and Dechezleprêtre show that an average 10% increase in the energy price difference would increase the EU imports of all sectors only by 0.2%. This impact is more considerable for energy-intensive sectors but energy price differences across time are able to explain less than 0.01% of trade flow variations. Moreover, a 65–115 €/tCO2 price of carbon in the EU ETS would also not have a significant impact on increasing the imports by 0.07% and decreasing exports by 0.2% [4]. Also, it is often argued that energy-intensive sectors are affected more but the analysis performed by Branger, Quirion, and Chevallier shows that there is no significant effect of the carbon price on net imports of steel and cement [6].

Although being grounded on precise empirical data, ex-post analyses are limited by the past situation as well as the scope and properties of the policies that were already implemented. The policies covered by empirical data are not extremely strict, and their cost fails to take a considerable share in the total cost structure of the most economic activities. Also, the real policies often already include some measures that prevent loss of competitiveness and carbon leakage (e.g., free allocation of emission allowances to energy-intensive sectors) [7]. Both changes in the policy design and business environment (e.g., level of trade restrictions) might affect the effects of carbon policies on competitiveness and carbon leakage. As noted by Arlinghaus, current levels and designs of carbon policies do not hurt competitiveness, but this does not necessarily mean that the same effect would be obtained with higher carbon prices or different policy designs [5].

Ex-ante analyses such as this case study provide model-based evidence, CGE models being the dominating approach in the field followed by sectoral partial equilibrium models and simple analytical models [7].

A meta-analysis on 25 ex-ante studies (in total, 310 estimates of carbon leakage ratios based on different models and scenarios) performed by Branger and Quirion has shown that the mean carbon leakage estimate is 14% (range from 5% to 25%) in scenarios without border cost adjustment. In other words, a reduction of 100 units of CO2 in the country that implements carbon regulation leads to an increase of about 14 units of CO2 in the rest of the world. This rate is about 6% (range from 5% to 15%) in scenarios with border cost adjustment. In contrary to partial equilibrium models, most CGE models show higher carbon leakage levels that remain even if border carbon adjustment is implemented. This is explained by the carbon leakage effects that are obtained through energy market channel that is not affected by border carbon adjustments and not covered by the most of partial equilibrium models [8]. Similar carbon leakage ranges up to 30% are also reported by other studies [9] [10].

Although some assumptions used in different models are rather similar and result in common carbon leakage trends [10], the analysis of the literature performed in COP21 RIPPLES project lists the fundamental assumptions that affect leakage rates in ex-ante studies. In energy market channel, fuel supply elasticity plays a major role. In competitiveness channel, key assumptions affecting leakage rates include returns to scale, homogeneity of goods, elasticities, capital mobility across sectors and regions, emission/sector coverage, and sectoral aggregation. For example, increasing returns to scale make economic activities more sensitive to policy measures and might increase the leakage rate. Technology spillovers are not modeled in the most of ex-ante analysis ant this might be one of possible explanations of divergence between the results obtained by ex-post econometric models and ex-ante analyses. In income channel, demand elasticity plays key role [7].

2. Current Policy Framework

2.1. Climate policies

There exist several different forms of climate policies. The IPCC [11] defines 8 different kinds of GHGs abatement policy instruments:

- Regulations and Standards (for example technology or performance standards necessary for emissions reduction)
- Taxes and Charges (a levy on undesirable activities)
- Tradable Permits (cap-and-trade systems, where aggregate emissions are limited)
- Voluntary Agreements (agreements between government and private parties on a voluntary basis)
- Subsidies and Incentives (direct payments, tax reductions etc.)
- Information Instruments (includes for example labelling programs and certification systems)
- Research and Development (investments for generation of innovative mitigation approaches)
- Non-climate policies (other policies which may significantly affect climate)

These policies can be categorized, according to Beestermöller [12], in fiscal (market-based instruments and investment support) and non-fiscal (regulatory and "soft" instruments), as shown in Figure 1.

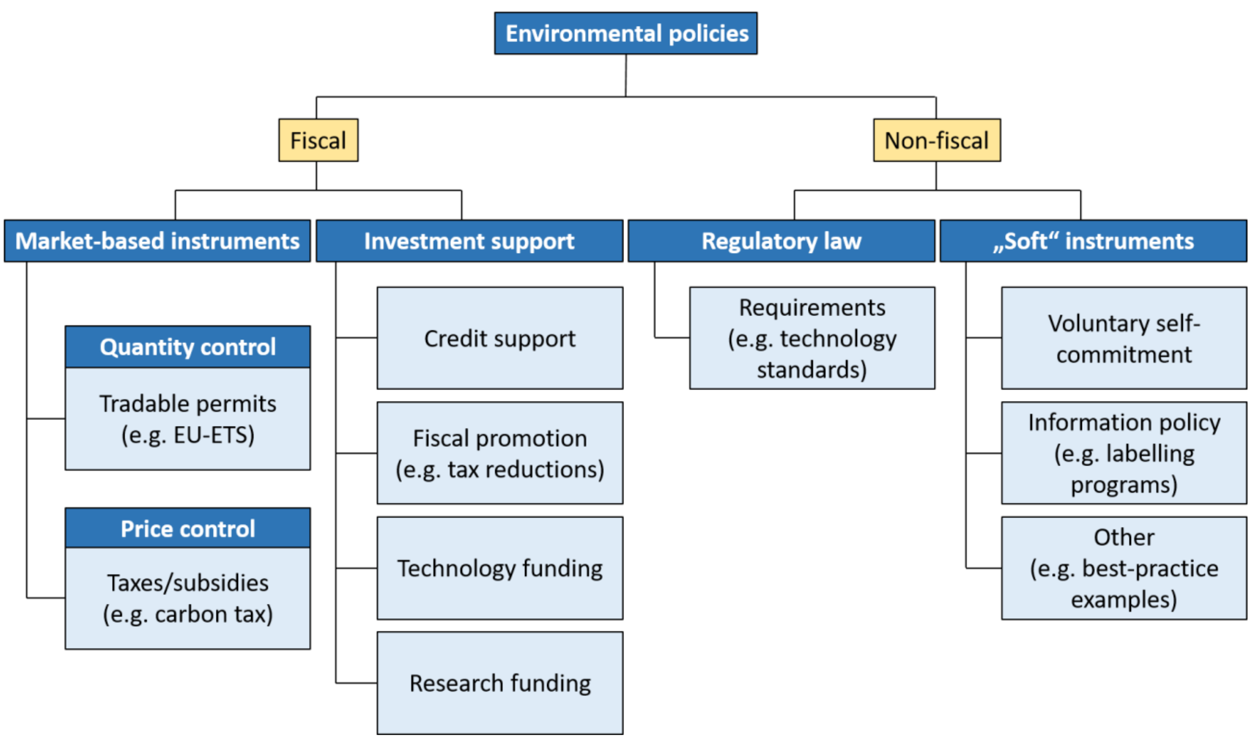

Figure 1: Categorization of policies

2.2. The actual state of policies in the EU

In 2009 the 2020 climate & energy package was enacted. Within this package three key targets were formulated [13]:

- Greenhouse gas emissions should be cut by 20% (compared to 1990)
- Renewables should account for 20% of the EU energy mix
- Energy efficiency should improve by 20%

In the long run there are even stronger reduction goals for GHG emissions, such as the 2050 Roadmap for a Low-Carbon Economy presents, where emissions should be 80% lower than the 1990 levels by 2050. Milestones were set by 2030 (40% reduction) and by 2040 (60% reduction) [14]. These targets are currently under revision for both the 2020 package (32% renewable, 32,5% energy efficiency by 2030) and the 2050 emissions reduction targets.

To meet these targets different measures have been taken. The most distinguished policy at an EU level is the EU Emissions Trading System (EU-ETS)[3]. The EU ETS is a market-based cap-and-trade system where the number of total emissions is limited by an aggregate emissions cap and the price is formed at the market by trading of CO_2 allowances. The EU ETS is organized in different phases and has built upon previous experiences to improve the current system. The scheme differs from other approaches by its wide coverage, being adopted by 31 different countries and covering up to 45% of the EU's GHG emissions [15].

However, the system has its flaws, most notably the structural allowance surplus which resulted in allowance prices between €8,00 and €6,00 in the period between December 2015 and January 2018 [16]. This price, however, was considered too low to encourage heavy polluters from undergoing long-term investments aiming at reducing their emissions and resulted in the creation of a market stability reserve for the next trading period, between 2020 and 2030 [17]. In order to increase the allowance price different measures have been taken: In phase 3 (2013 – 2020) most of the allowances are allocated via an auctioning process instead of being allocated for free [15]. Furthermore, the current surplus of emission allowances is addressed in the short-term by back-loading of auctions from 2014 – 2016 to 2019 – 2020 and in the long-term by introducing a market stability reserve. The market stability reserve will operate as of January 2019 and will absorb the 900 million back-loaded allowances. During Phase 4 of the EU-ETS, between 2021 and 2030, unallocated allowances will then be transferred to the reserve and thus be withdrawn from the market [18]. This is expected to result in higher market prices.

For the non-ETS sectors, there exists the Effort Sharing Decision, which obliges Member States of the EU to fulfill national emission targets for 2020. The EU-wide emission target is a reduction of emissions

[3] In several other regions there do exist cap-and trade systems as well. For an overview see https://icapcarbonaction.com/en/

by 10% compared to 2005. National emission targets have been set relative to the GDP per capita of each Member State and range from a 20% reduction for the richest EU countries to a 20% increase for the least wealthy one. Although less wealthy countries are allowed to increase their emissions, the emission growth limit requires an emission reduction effort given the current emission projections. The national policies necessary for accomplishing with the emission targets have to be defined and implemented by each Member State [19]. From 2021 – 2030, the Effort Sharing Decision will be followed-up by the Effort Sharing Regulation, which sets an overall emission reduction target of 30% compared to 2005. National emission targets are again relative to GDP per capita and will range from a 0% to a -40% reduction [20].

Furthermore, the share of renewables in energy consumption for each Member State is determined in the Renewable Energy Directive. National targets vary between a 10% and a 49% increase. In a similar manner, the energy efficiency target is addressed through the Energy Efficiency Plan and the Energy Efficiency Directive [13].

2.2.1. Policies to address carbon leakage

Since the shift of production activities to other countries and its effect on competitiveness is considered particularly relevant, different policy measures exist in order to prevent carbon leakage and protect vulnerable industries. Obviously, the most straightforward measure to avoid carbon leakage to other countries would be a worldwide carbon policy unification. However, it would be difficult to adopt unified policies due to heterogeneous structures of the economies and differences in policy priorities in the countries. Therefore, some soft measures and targeted support for developing countries are used.

Carbon policy alleviation for particular industries or installations is the most direct measure aiming at carbon leakage prevention. It can be realised for example by allocation of free emission allowances to specific facilities or by creating a so-called carbon leakage list as it is the case in the European Union. Carbon leakage list covers industries that are especially vulnerable to carbon leakage. The industry sectors on the carbon leakage list are exempted from the regular ETS auctions but rather receive a share of their emission allowances from free allocation. However, free allocation of emission allowances weakens the carbon policy itself or increases the burden on the sectors not covered by this carbon leakage prevention measure.

Another direction to avoid carbon leakage is targeted financial compensations to the companies that lose their competitiveness. Such compensations are especially sensitive due to competition distortions they cause in the industry. To create level playing field for different market participants and prevent emission increase, financial compensations are often offered on competitive basis for the entities that invest in emission reduction.

A group of measures are used to keep carbon unconstrained products (i.e., products from countries without or with weak carbon policy) in the same or similar competitive position compared with domestic production as it was before the introduction of carbon policy. These measures are realized as various import restrictions for products from the countries that do not implement similar carbon policies. The list of such import restrictions includes border cost adjustments, quotas, technical regulations and standards, and others [21]. Although border adjustments are often called “border tax adjustments”, such notation is too strict since it is often related with the existing carbon policy and might be realized by requiring to buy certain amounts of allowances rather than paying taxes [3].

3. Methodology

3.1. Modelling Framework

In order to analyze the relevance and the consequences of carbon leakage the numerical model NEWAGE (National European Worldwide Applied General Equilibrium) was applied. NEWAGE is a recursive-dynamic general equilibrium model with special focus on the energy sector. It describes the macro-economy through production functions and depicts interdependencies between different sectors within an economy as well as interdependencies among different economies.

NEWAGE covers the entire World, however, most countries are aggregated into regions. In total there are 18 regions, 9 within Europe, 9 outside of Europe. Similarly, production sectors are represented at certain aggregation level. There are 5 sectors belonging to the energy production, 6 sectors belonging to the energy-intensive industry, 3 sectors representing rest of industry and 4 sectors representing the rest of the economy. Within the electricity sector 18 generation technologies are included. Production possibilities are represented through constant elasticity of substitution (CES) production functions. Appendix A.2 presents detailed information regarding NEWAGE's regional and sectorial structure, as well as the CES nesting for sectorial and electricity production.

While energy system models are generally better suited to analyze the energy sectors in detail they lack the relations with other sectors and are not able to assess overall macro-economic costs. With NEWAGE the impact of different political interventions on macro-economic indicators, such as GDP growth, employment or competitiveness can be assessed. Therefore, NEWAGE is a valuable tool for the analysis of carbon leakage and its' effect on competitiveness and hence was chosen as the most suitable modeling framework for this case study.

3.2. Model's limitations

Despite being able to represent the relationship between sectors in the economy, NEWAGE presents limitations that influence the final results of this analysis and have to be explained. The main drawbacks from the model can be divided in two categories, lack of endogenous technology development and inability to internalize positive externalities caused by environmental policies.

The first limitation refers to NEWAGE's flexibility when facing high energy costs. The actual version lacks endogenous technology development, which translates as the capacity to invest on increasing the efficiency of production technologies, making them consume less energy for the same output. In the case of the electricity sector, it means that through investments in research and development there is a reduction in the capital cost or the fuel consumption to produce one unity of energy. In order to surpass this limitation, NEWAGE utilizes exogenous assumptions for the technology development from 2011 and 2050 through the AEEI parameter, which is better explained in section 4.3. For this work the same set of AEEI was applied in all scenarios, meaning that regardless of the environmental ambition, the technology development happens in the same pace.[4]

Finally, in the present state of NEWAGE it sees the gains and losses of any policy measure solely as a matter of profit and costs. For the present work it means that the model is not capable of accounting the non-financial benefits brought by environmental policies, such as increased air quality or lower water pollution.

It is important, therefore, to understand that due to its limitations the figures produced by NEWAGE, especially for economic development, are rather pessimistic. This happens because the model fails to account for non-financial gains from tighter emission targets, such as higher life quality and faster technology development.

3.3. Stakeholders' integration

One of the central pillars of the REEEM project, as well as the other Horizon 2020 funded projects, is the strong relationship with stakeholders and this study also made usage of this cooperation. The main contributions from stakeholders to this work were done in two opportunities, first through the workshop "Energy transition pathways for the EU" held in October 2017 and focused on defining future states for the EU and the rest of the World, as well as pathways to reach a low-carbon EU. One of the main results of this workshop was the definition of the REEEM pathway, which congregates the main assumptions of this project regarding how the world will develop in the coming years. The relevant assumptions from the REEEM pathway to this work will be highlighted in section 4.4 (scenario definition).

The second main contribution from stakeholders to this work was made in April 2018 through the workshop "Macroeconomic projections for the European Union until 2050", where the preliminary results of this analysis were shown to a group of selected stakeholders from industry, academy and the European Commission. By the end of the meeting, the main request of the attendees was to add one extra policy to the ones being analyzed, the free allocation of ETS allowances as part of the European Commission's policy to support industrial installations exposed to a significant risk of carbon leakage. A description of this policy and how it was implemented in this analysis will be given in section A.4.

3.4. Modelling assumptions

Although NEWAGE covers the whole economy and all world regions, reality is still far too complex to be captured adequately. Consequently, and as in any other numerical model, several assumptions on

[4] Since the exogenous representation of technological change does not capture the respective dynamics well, NEWAGE will be improved to endogenously account for these shortcomings. Endogenous technological change can be implemented differently in CGE models. An overview of different methodologies for implementation can be found e.g. in Gillingham et al. [38] or Löschel [36].

certain boundary conditions are employed. For the sake of transparency, the main assumptions are revealed, documented and justified in the next paragraphs.

Elasticity of Substitution (EoS)

A central assumption influencing the choice of production factors and technologies are the EoS parameters. They define how easily production factors, e.g. capital and labor, or different technologies, e.g. solar and wind electricity, can substitute each other[5]. Substitution parameters vary between 0 and infinity, with a value equal to 0 meaning substitution is not possible. The higher the elasticity value, the easier it is to substitute the two respective factors. The elasticity parameters in NEWAGE are mainly based on Beestermöller (2016) [12] and are summarized in Table 8 to Table 11 in appendix A.3 .

Further assumptions

In addition to the aforementioned assumption, the following sources were used for a number of assumptions:

- GTAP 9 Data Base [22]
    - Trade and energy data on year 2011
- Electricity Information 2013 [23]
    - Electricity generation per country on the year 2011
- EU Reference Scenario 2016 [24]
    - GDP growth for the EU-28 regions between years 2011 and 2050
    - CO_2 emission for the EU-28 regions between years 2011 and 2050
- The Great Shift: Macroeconomic projections for the world economy at the 2050 horizon [25]
    - GDP growth for the non-EU-28 regions between years 2011 and 2050
    - CO_2 emission for the non-EU-28 regions between years 2011 and 2050

CO_2 emission trajectory

Moreover, the CO_2 emission trajectory is a central premise and it varies depending on the scenario being analyzed. For each of the regions in the Rest of the World there is a defined CO_2 emission trajectory defined according the World dimension, as shown in Table 1. For the regions within the EU-28, the CO_2 trajectory is defined according to the policies being utilized, which can be visualized on section 4.5.2. Appendix A3 contains more detailed information of CO_2 emission trajectory for specific regions and states.

3.5. Scenario definition

The process of selecting scenarios for this case study focused primarily on finding a wide enough range of possible World and EU states that allow for a better understanding of effects regarding competitiveness and carbon leakage. First, it was necessary to define directions in which the European

[5] A graphic illustration of this CES structure can be found in the appendix

Union and the rest of the World would develop, in terms of environmental ambition and cooperation, until 2050, as it plays an important role on defining which policies will be applied. Each of these possible directions, in this work, will be called a state. There are four states for the Rest of the World and three for the European Union. Following, a number of policies were chosen for the most relevant combinations of states from the EU and the Rest of the World.

3.5.1. World and European states

World dimension

The World dimension describes the level of climate ambition in regions outside the EU-28. The possible states for the World dimension can be described as follows:

Table 1: Scenarios - World states

W0: No ambition	W1: Business as Usual	W2: Regional push	W3: 2°C
No emission targets.	Emissions follow the Reference Technology Scenario from the Energy Technology Perspectives (ETP) 2017 [26].	A selected group of regions follows the 2°C target scenario. Remaining regions follow the Business as Usual scenario.	Emissions follow the 2DS Scenario from the ETP 2017 (ETP) [26].

European dimension

Similarly, the European dimension describes the level of climate ambition within the EU-28 member states. The possible states for the European dimension can be described as following:

Table 2: Scenarios - European states

E1: Business as Usual	E2: Cluster Union	E3: Stronger Union
Europe follows the rationale of Scenario 1 from the White paper [27].	Europe follows the rationale of Scenario 3 from the White paper [27], meaning that selected countries have more ambitious targets. While targets for ETS sectors remain identical for members of the Cluster Union and other EU countries, the non-ETS targets differ. Membership in the Cluster Union depends on socio-economic and energy-related indicators as well as on geographic location. See Appendix A3 for more information on this scenario.	Europe follows the rationale of Scenario 5 from the White paper [27], meaning that all member states increase their cooperation across all policy areas.

3.5.2. Policy measures

In addition to the aforementioned states, it is necessary to precisely define the policies implemented in order to reach those overall targets. Since the EU ETS is currently the main policy instrument on EU level to cut GHG emissions, we assumed it also to be the main policy implemented in the different scenarios. Additionally, the Effort Sharing Decision (ESD) was used as a complementing policy for the non-ETS sectors.

Finally, the policy measures analyzed in this work consider a number of variations for the EU-ETS. These alternative versions differ from each other by a number of parameters, such as the emission reduction target in 2050, the number of sectors included in the trading system and, in some cases, a maximum allowance price. There are also different reduction targets for the ESD sectors. All those different policy options can be summarized as follows:

- **ETS-BaU**
  - This policy scenario represents the current state of the EU-ETS. The NEWAGE sectors included in this version of the ETS are oil refining, electricity and the energy intensive industry, except for food and tobacco.
  - The GHG reduction target was taken from the EU reference scenario 2016 [24] and it considers that in 2050 there will be a reduction of 47.4%, compared to 1990 levels.
- **ETS-80**
  - Same sectorial reach as ETS-BaU
  - GHG reduction target of 80% in 2050 compared to 1990 levels.
- **ETS-90**
  - Same sectorial reach as ETS-BaU
  - GHG reduction target of 90% in 2050 compared to 1990 levels.
- **ETS-95**
  - Same sectorial reach as ETS-BaU
  - GHG reduction target of 95% in 2050 compared to 1990 levels.
- **ETS-all-80**
  - All 18 sectors of NEWAGE and households' consumption are included in the ETS and participate of the cap-and-trade system.
  - Overall GHG reduction target of 80% in 2050 compared to 1990 levels.
- **ETS-all-90**
  - All 18 sectors of NEWAGE and households' consumption are included in the ETS and participate of the cap-and-trade system.
  - Overall GHG reduction target of 90% in 2050 compared to 1990 levels.

- **ETS-all-95**
    - All 18 sectors of NEWAGE and households' consumption are included in the ETS and participate of the cap-and-trade system.
    - Overall GHG reduction target of 95% in 2050 compared to 1990 levels.
- **Price Collar – 80 (ETS-PC-80)**
    - This policy is always applied in addition to the **ETS-80**, and never alone. The concept of a price collar is to set a maximum and a minimum price for the CO_2 certificate, so it does not become too expensive for the actors that have to buy, nor too cheap that investment in new technologies is not made.
    - For this analysis, the **price collar – 80** sets the maximum CO_2 certificate price as **80%** of the price reached for the policy ETS-80.
    - In practical terms, when the maximum price is reached, more allowances are brought into the market, thus increasing the supply, causing the equilibrium price to hold at 80% of the price from policy scenario ETS-80.
    - Same sectorial reach as ETS-BaU
- **Price Collar – 90 (ETS-PC-90)**
    - This policy is always applied in addition to the **ETS-80**, and never alone.
    - For this analysis, the **price collar – 90** sets the maximum CO_2 certificate price as **90%** of the price reached for the policy ETS-80.
    - In practical terms, when the maximum price is reached, more allowances are brought into the market, thus increasing the supply, causing the equilibrium price to hold at 90% of the price from policy scenario ETS-80.
    - Same sectorial reach as ETS-BaU
- **ESD-BaU**
    - This policy scenario represents the current emission reduction targets for the non-ETS sectors. The targets until 2050 were taken from the EU reference scenario 2016 [24].
- **ESD-New**
    - This policy scenario is part of the REEEM pathway and represents the project's assumptions for how the ESD emissions will reduce until 2050. The regional emission targets can be found in appendix A.3, Table 14.
- **Free Allocation of Allowances (FA)**
    - Similar to the price collar policy, this cannot be applied alone, but always as a supplement to an existing ETS policy. In this work, the FA will be applied in two cases: in the status-quo pathway and the REEEM pathway. More information regarding the application of this policy in the model can be found at appendix A.4.

3.5.3. Scenario construction

From the different World states, EU Member-States and policy options defined above numerous scenarios can be built by combining the different states and assigning policy options to the obtained combinations. In order to gain insights on carbon leakage and competitiveness several relevant combinations were then selected.

For analyzing carbon leakage, the main focus is the shift of CO_2 emissions between regions or sectors. This will depend highly on the overall European climate ambition but not on the specific portfolio of policies. In contrast, for competitiveness the choice of policy may have a considerable influence on countries' and, especially, sectors' performance. Consequently, different combinations were analyzed to tackle those two aspects of analysis.

Table 3 shows all the scenarios constructed and indicates whether the respective scenario was used for analysis of carbon leakage, competitiveness or both.

Table 3: Scenarios constructed

World / EU	W0: No ambition	W1: Business as Usual	W2: Regional push	W3: 2°C
E1: Business as Usual	ETS-BaU + ESD-BaU	ETS-BaU + ESD-BaU ETS-BaU + ESD-BaU + FA	ETS-BaU + ESD-BaU	
E2: Cluster Union	ETS-80 + ESD-new ETS-90 + ESD-new ETS-95 + ESD-new ETS-PC-80 + ESD-new ETS-PC-90 + ESD-new	ETS-80 + ESD-new	ETS-80 + ESD-new ETS-80 + ESD-new + FA ETS-90 + ESD-new ETS-95 + ESD-new ETS-PC-80 + ESD-new ETS-PC-90 + ESD-new	ETS-80 + ESD-new
E3: Stronger Union	ETS-all-80 ETS-all-90 ETS-all-95	ETS-all-80 ETS-all-90 ETS-all-95	ETS-all-80 ETS-all-90 ETS-all-95	ETS-all-80 ETS-all-90 ETS-all-95

3.5.4. Central pathways

In order to facilitate communication of results and guarantee assumptions harmonization within the different research groups of the REEEM project, a number of pathways were defined. They represent a set of assumptions for several different dimensions, such as World, European, Environmental, Social and Political.

For this work there are two main pathways, status-quo pathway and REEEM pathway. Their description, using only the dimensions relevant for the present analysis (World, European and Policy Measures) are as follow:

- **Status-quo Pathway**
    - World Dimension: Business-as-Usual (W1)
    - European Dimension: Business-as-Usual (E1)
    - Policy Measures: ETS-BaU + ESD-BaU

- **REEEM Pathway - Represents REEEM's central assumptions for the future**
    - World Dimension: Regional Push (W2)
    - European Dimension: Cluster Union (E2)
    - Policy Measure: ETS-80 + ESD-New

4. Modeling results

This section highlights the main results obtained from the modeling exercise done with NEWAGE. It is important to highlight the fact that, due to the large number of scenarios and results, only the ones relevant to the scope of this work will be shown.

First there will be shown the relationship between emissions reduction and GDP growth for the EU-28. This first part will introduce the concept that a higher environmental ambition comes with certain costs for the economy. The second part focus on how the production of emissions shifts from the EU to other regions when the European ambition level increases. Following, numbers for emission produced within the EU are shown, together with the effects on different industrial sectors.

The last two sections will mainly focus on measures to alleviate the negative economic effects of limiting emissions, first by electrification and, second, through the free allocation of allowances, which is a policy currently being applied in the EU.

4.1. Relationship between emissions reduction and GDP growth

In general, our results suggest that there exists a negative relationship between CO_2 emissions reduction in 2050 relative to 1990 and GDP growth of the EU28 in 2050 relative to 2011. This indicates that higher CO_2 emission reduction efforts come along with a decrease in GDP growth, as can be seen in Figure 2, where all the scenarios calculated were sorted according to their respective CO_2 emissions reduction and their GDP growth. The results indicate that cutting CO_2 emissions by 80% compared to 1990 levels in 2050, instead of following the actual path, can make GDP growth decrease from roughly 80%, compared to 2011 level, to around 50%.

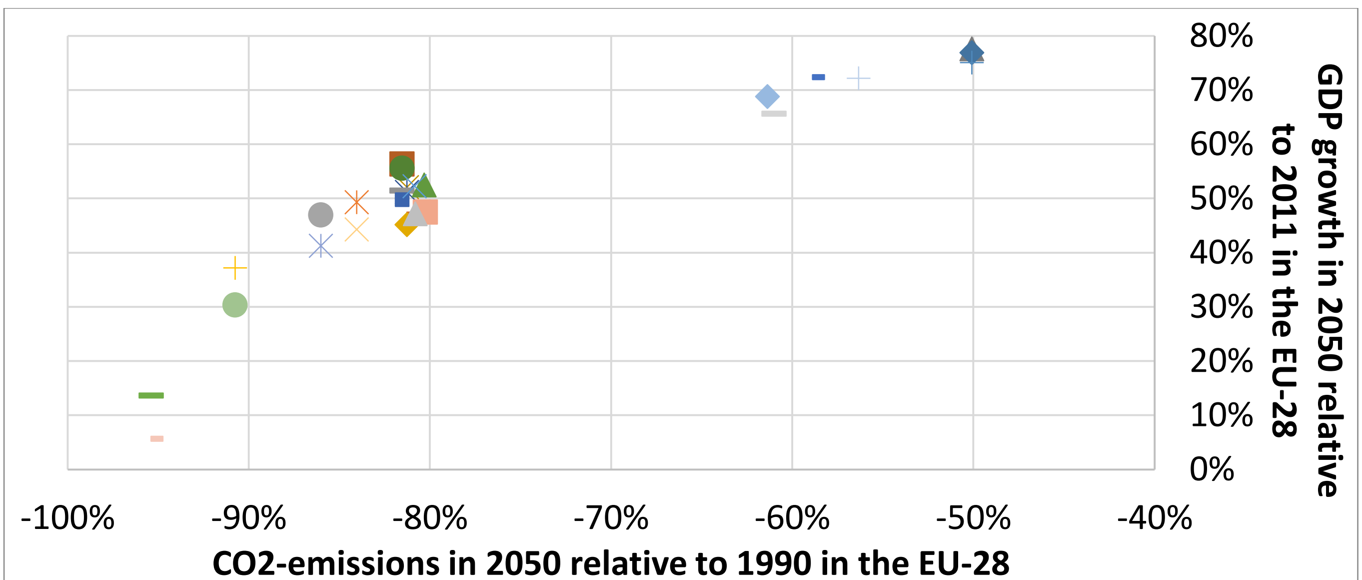

Figure 2: GDP growth versus CO_2 emissions reduction for all scenarios from this study in EU-28.

This negative relation holds for different ambition levels on the European as well as on the World dimension. In case the EU is assumed to have a fixed climate ambition but world ambition increases, e.g. from the “no ambition” state to the “regional push” state, this causes the EU-28 GDP growth to be reduced between 2 and 5%, as shown on Figure 3, shows exactly how much the environmental ambition on the regions outside of the EU-28 influence GDP development for different policy measures inside the EU-28.

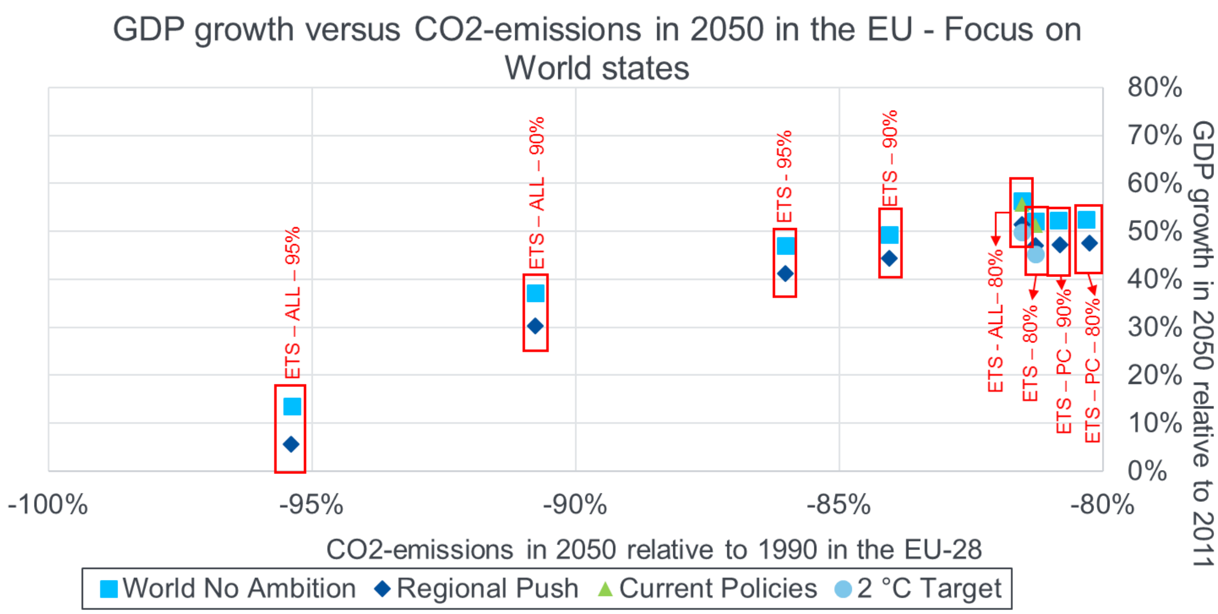

Figure 3: Relationship between GDP growth and CO2 emissions reduction with distinction of EU policies and world ambition

Note, however, that NEWAGE does not consider positive externalities from emissions reduction. If emissions are reduced air and water pollution as well as the risk for natural disasters decrease and thus, positive impacts on the environment and on health and thereby positive effects on the economy in the long term can be expected.

4.2. CO_2 production outside of the EU-28

As mentioned before, carbon leakage threatens the efficiency of environmental policies, as the emission cut in one region may shift to another one with lower environmental standards. Figure 4[6] shows how total CO_2 emissions in the EU-28 and in the entire World change considering four different European emission targets. For this analysis, only World dimension **W0** was considered, meaning that the non-European countries had no emission targets and, hence, no upper limit for their emissions. From the difference between EU-28 and World emissions for the same year and emission target it is possible to assess the shift in CO_2 production from EU-28 to other regions.

[6] Scenarios which description contains “XX% Red All Sectors” refer to the policy “ETS-all-XX”, as described in section 4.5.2.

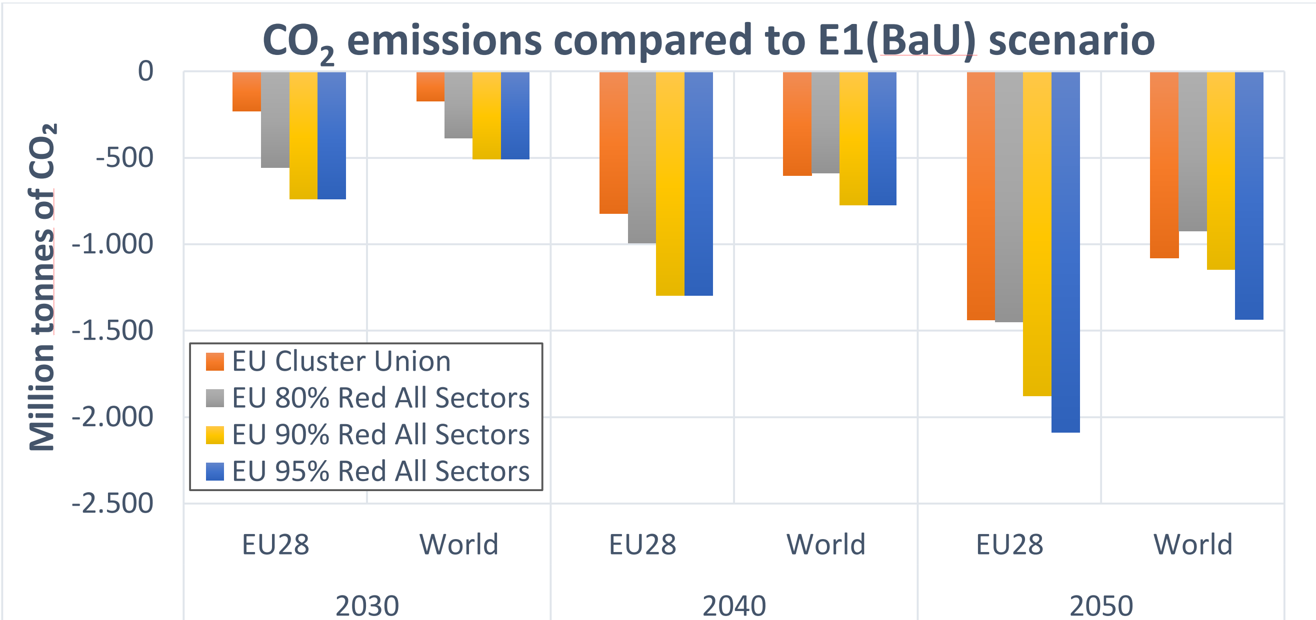

Figure 4: Difference in the CO2 emissions between the E1(BaU) and other emission targets for EU-28

Table 4 shows the CO2 reduction between 2011 and 2050 for different European emission targets both for the EU-28 and the entire World. As in Figure 4, these results are for World dimension **W0**, which considers that there are no emission targets outside of the EU-28. The further right column, Delta (%), indicates the percentage of CO_2 that is leaking from Europe. The results indicate that although the two first scenarios, EU Cluster Union and ETS-all-80, reach very similar reduction within Europe, in the second case the leakage is roughly 50% higher. Additionally, the total leakage remains between 25 and 39%.

Table 4: Emission reduction (Mt CO_2) in 2050 relative to 2011

Scenario	EU-28	World	Delta	Delta (%)
EU Cluster Union	-1438,6	-1080,2	358,4	24,9%
ETS all 80%	-1450,1	-922,9	527,3	36,4%
ETS all 90%	-1876,0	-1146,9	729,1	38,9%
ETS all 95%	-2089,0	-1435,6	653,4	31,3%

With respect to specific regions, as seen on Figure 5[7], the results indicate that CO_2 from the EU-28 mainly leaks to the USA and remaining OECD countries, which can be explained as a shift of the European

[7] Scenarios which description contains "XX% Red All Sectors" refer to the policy "ETS-all-XX", as described in section 4.5.2

production to these regions, since they compete in the same high value sectors, while there is a lower leakage to the BRICS countries.

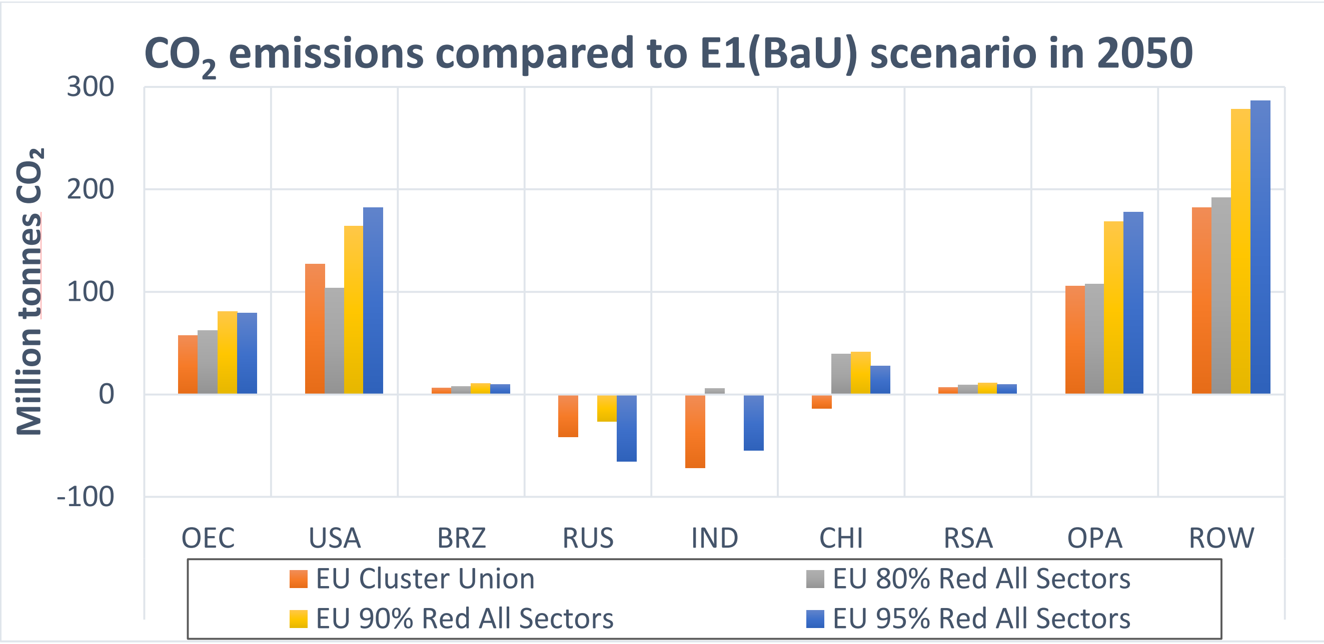

Figure 5: CO_2 emissions in regions outside of the EU-28 in the year 2050

4.3. Impacts within EU-28

Figure 6[8] provides a closer look at the sectorial CO_2 emissions in the EU-28 considering five emission targets. For scenarios EU Cluster Union and EU 80% RED ALL SECTORS, where total emissions are identical, the share of emissions for different sectors is, however, notably different. While in both scenarios households and transportation sectors have the highest share of total EU emissions, contribution from the different sectors vary greatly. As Figure 6 shows, in the ETS-all-80 scenario, where, contrary to the Cluster Union scenario, ETS and non-ETS targets are identical, the share of emissions for households, services and transportation sectors increases by 5, 2 and 9%, respectively. Conversely, for electricity and industry sectors the share of emissions decreases by 11 and 5%. Hence, emissions leak from the latter to the former due to differing relative reduction costs if reduction targets cover all sectors equally.

[8] Scenarios which description contains “XX% Red All Sectors” refer to the policy “ETS-all-XX”, as described in section 4.5.2

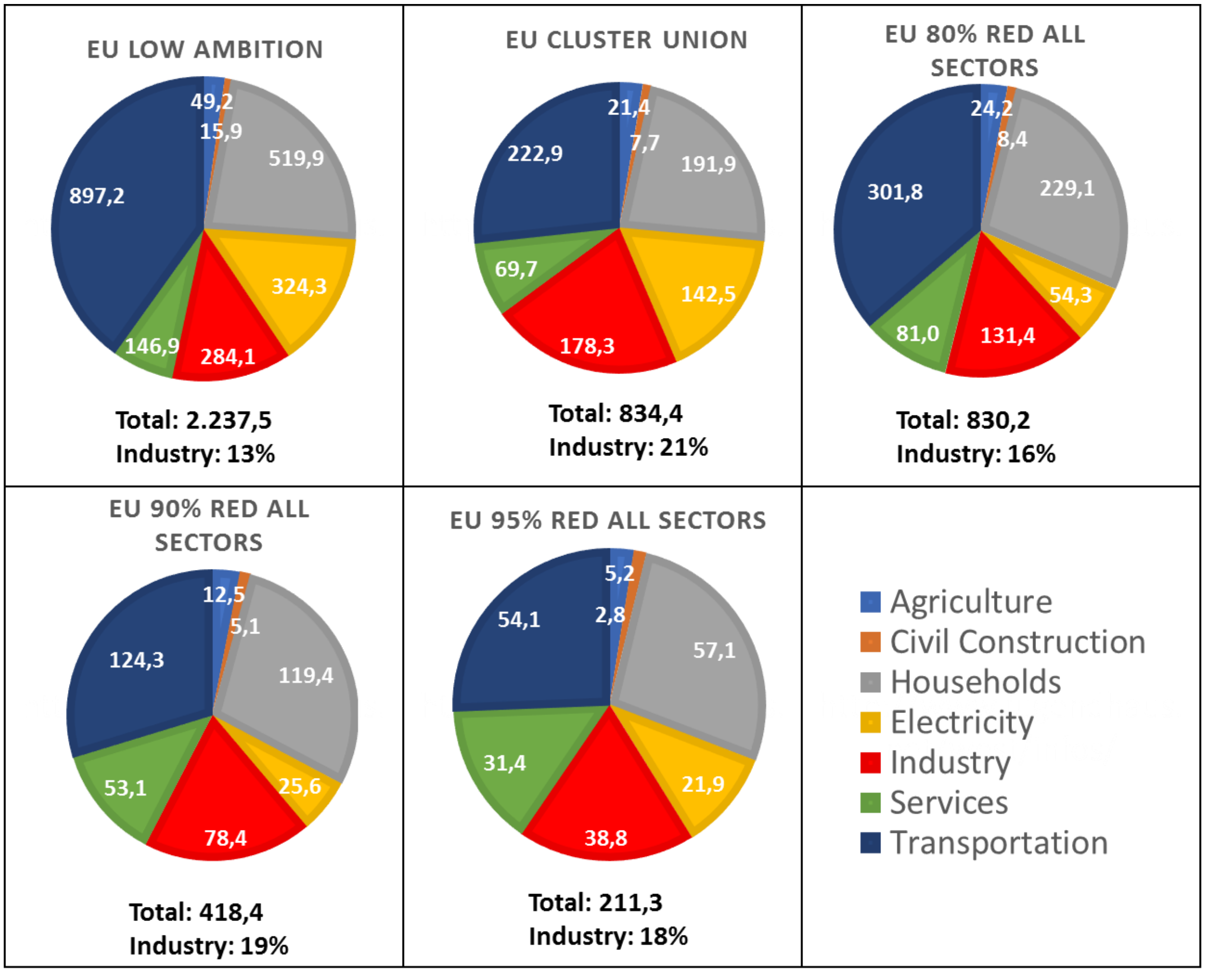

Figure 6: CO2 emissions per sector in 2050 in the EU-28

4.3.1. Gross value added – European policies

In addition to the results regarding emissions produced by each sector, the production of each sector is also impacted by different emission targets. Figure 7 considers six different policy measures, all applied in combination to World state W2 (Regional push). For this analysis a different World State was chosen, compared to the previous results, so that the sectoral output could be measured in the context of the REEEM pathway. For this results, the EU Cluster Union state (E2) with policies ETS-80 and ESD-new is the reference (100%), and the values for the other scenarios are shown in relative terms.

The results suggest that the price collar policies have a small positive impact over the GVA of the energy intensive sectors, especially iron and steel, non-ferrous metals and non-metallic minerals, while having almost no effect over the other sectors. However, limiting the maximum allowances' price has the disadvantage of reducing the emissions' reduction and, thus, the group of sectors within the ETS would not reach the emission targets planned for 2050.

Increasing the emission cuts in the ETS sectors (ETS-90 and ETS-95), as well as and the inclusion of all sectors in the ETS (ETS-all-80) do have a negative impact on the GVA of energy intensive sectors. The most affected sector is iron and steel, with an output close to half of the reference, and chemistry, non-ferrous metals and non-metallic minerals losing between 22 and 32% of its production compared to the reference.

While the energy intensive sectors are heavily affected by higher CO_2 reductions, the effects on remaining sectors are very low. Considering only machinery and vehicles, which represent a high share of the European GDP, the highest loss in GVA is around 2.15%.

These results indicate that higher CO_2 reduction in the ETS sectors or adding all sectors and the consumption to the ETS policy have negative effects to the energy intensive sectors, with exception of food and tobacco. Additionally, the economy would be much more dependent of the machinery and vehicles sectors, as the impact over them is very low. Finally, if keeping the competitiveness in the energy intensive sectors high is a priority, the results suggest that it can only be achieved by the creation one or more extra measures focused exclusively on these sectors, since their output is reduced by increased CO_2 reduction.

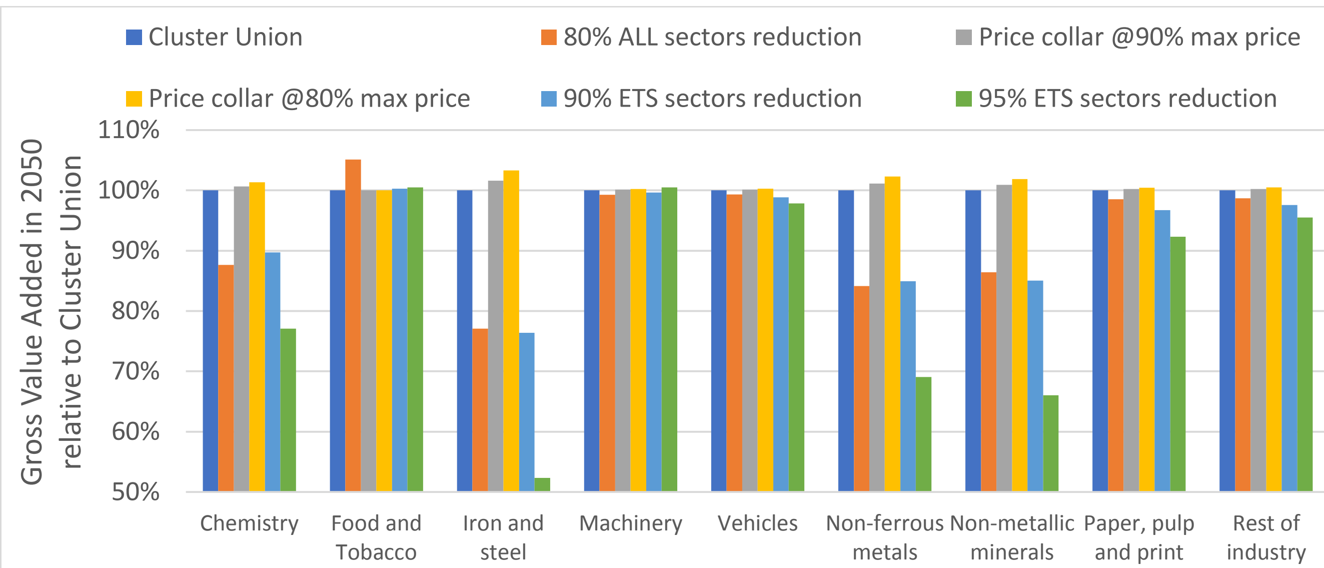

Figure 7: Gross Value Added in 2050 in the EU-28 for different sectors and EU ambition levels and policies

4.3.2. Gross value added – Emission targets outside of the EU-28

For Figure 8 it was considered the same configuration for the EU-28, Cluster Union, with different emission targets for the remaining regions of the World. As an effect of these different targets, the results suggest that the energy-intensive sectors, which were negatively affected by stronger EU ambitions, do react positively to stronger world ambitions with GVA increasing between 8 and 42% when comparing the "W3: 2°C" scenario to the "W0: No ambition" base case. The GVA of the remaining sectors, however, decreases between 2 and 11%, for the same scenario comparison. It can thus be concluded, that higher world climate ambition has positive effects on the international competitiveness of European energy intensive sectors due to increased CO_2 emission costs while the resulting decrease in world economic growth leads to production declines in more export oriented sectors.

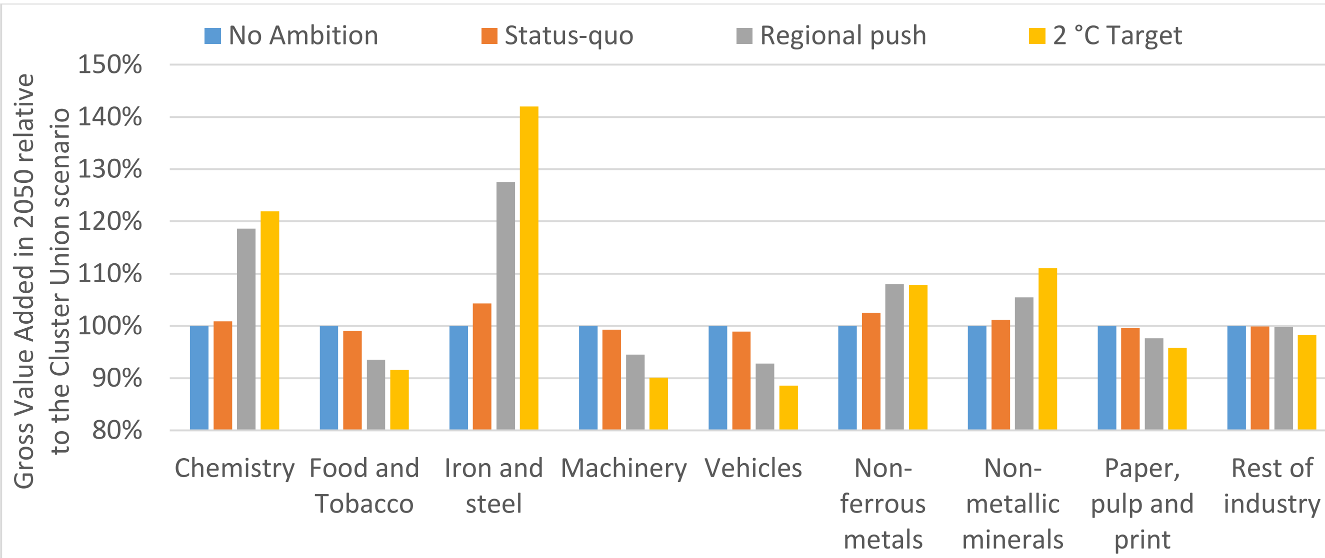

Figure 8: Gross Value Added in 2050 in the EU-28 for different sectors and world ambition levels

4.4. Electrification

GDP can be positively affected if substitution between fossil fuels and electricity is more flexible. Figure 9 shows the growth in EU's GDP for the REEEM Pathway (W2 +E2) from 2011 to the years between 2030 and 2050 for three different values of Elasticity of Substitution (EoS) between fossil fuels and electricity. The EoS values used for this analysis are 0.1, which represents the original assumption, 1 and 10. Note that for each value of elasticity, the substitution between fossil fuel and electricity is made more flexible.

While for the year 2030 the different values of EoS do not play a significant role on the GDP development, for the later years this statement is not valid. Especially for the year 2050, when there are less CO_2 allowances available in the market, the flexibility in which fossil fuel can be substituted by electricity plays a major role in the GDP development, as an EoS of 1 increases the GDP development in 5%, compared to the original assumption, and an EoS of 10 increases the GDP development in 20%, also compared to the original assumption. Therefore, fostering and facilitating electrification can be seen as a major contribution to alleviate the transformation of the energy system.

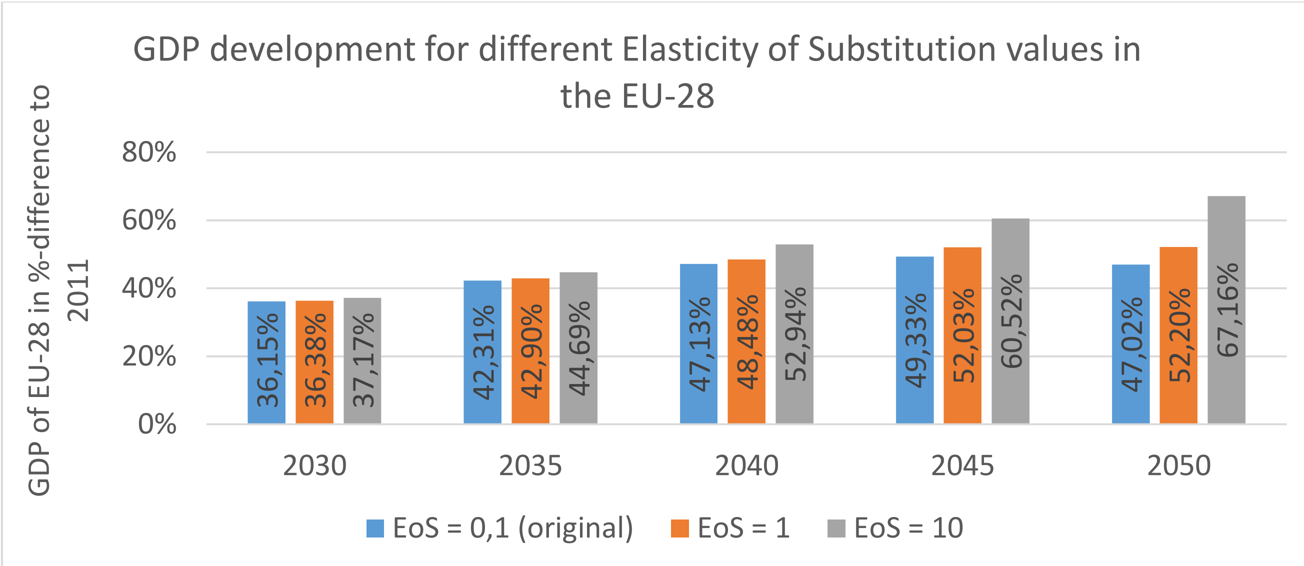

Figure 9: GDP of EU-28 in %-difference to 2011 for different substitution elasticities (EoS in REEEM Pathway = 0.1)

Regarding the effects of electrification in industrial GVA, they depend highly on the European climate ambition, as shown in Figure 10. While for the Cluster Union specification (80% reduction target, ETS and non-ETS sectors, see first three scenarios in Figure 10) effects are mostly negative due to increased electricity consumption resulting in higher electricity prices, since electricity consumption increases. Effects are positive, however if European ambition increases (90% reduction target, ETS covering all sectors, see last three scenarios in Figure 10). Therefore, with increasing climate ambition electrification plays a central role for securing competitiveness.

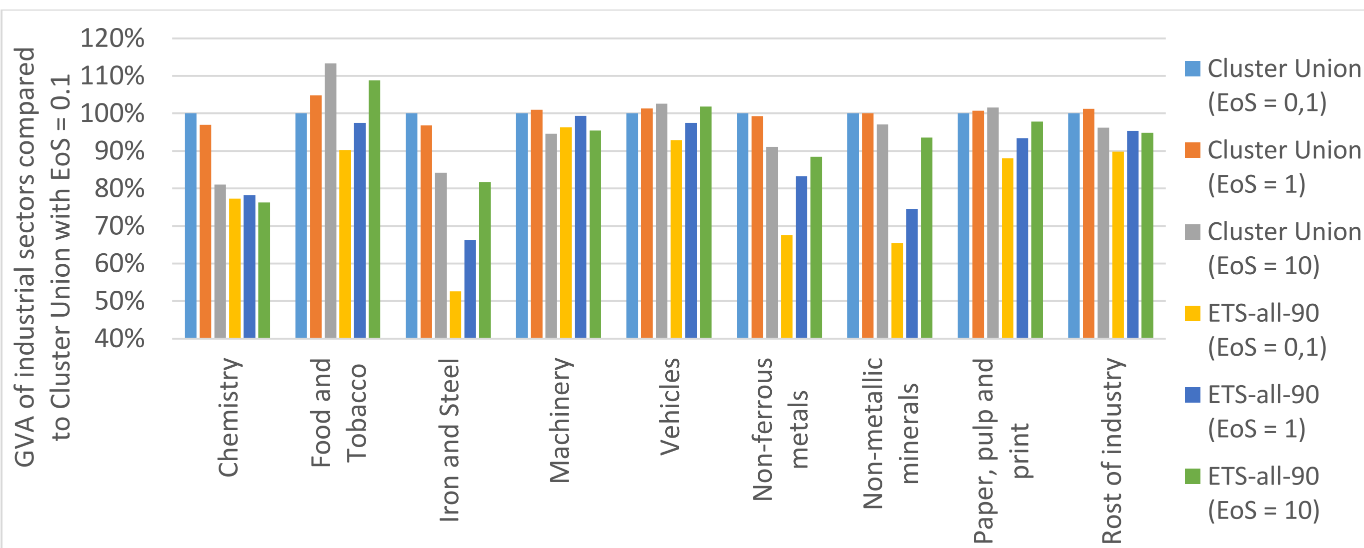

Figure 10: Gross Value Added in 2050 in EU-28 for different sectors, scenarios and elasticities of substitution (Cluster Union (EoS = 0.1) = 100%)

4.5. Effects of the free allocation of allowances

The results on the effects of free allocation of allowances are divided in two parts. The first presents the difference between scenarios **E1W1 (ETS-BaU + ESD-BaU + FA)** and **E1W1 (ETS-BaU + ESD-BaU)**, as well as the difference **E1W2 (ETS-BaU + ESD-BaU)** and **E1W1 (ETS-BaU + ESD-BaU)**, so it is possible to assess which aspect has more influence over the economic activity in the industrial sectors, whether internal policies or external emission cuts. Following, the difference between the REEEM Pathway with and without free allowances policy, more precisely scenarios **E2W2 (ETS-80 + ESD-new + FA)** and **E2W2 (ETS-80 + ESD-new)**, in order to verify if the free allocation policy has a higher degree of impact when applied in a scenario with a higher environmental ambition. In both sets of results, the parameters displayed are for the EU-28.

The first set of results, depicted in Table 5, indicate that the Free Allowance scenario has a slightly higher potential GDP growth than E1W1 (ETS-BaU + ESD-BaU) and E1W2 (ETS-BaU + ESD-BaU). As for the GVA, the results depend on the year. In 2030, when the share of Free allowances for the energy intensive sectors vary between 50 and 100%, the output of these sectors is indeed higher for E1W1 with free allowances and E1W2, while the remaining sectors, especially machinery and motor vehicles, which have a high share of contribution to EU's GDP, see a lower output decrease in E1W1 with free allowances than E1W2.

For the year 2050 only two sectors have lower output in scenario E1W1 with free allowances compared to E1W1, chemistry and food and tobacco. For scenario E1W2, however, there is a considerable increase in the GVA of energy intensive sectors, with the exception of paper, pulp and print, but sectors with a higher share of the total European production end up decreasing their output, which causes the lower potential GDP growth in this scenario.

Table 5: Results for Free Allowance scenario against E1W1(BAU) and E1W2 in the EU-28

Year	**2030**		**2050**	
Scenario	**E1W1 (ETS-BaU + ESD-BaU + FA)**	**E1W2 (ETS-BaU + ESD-BaU)**	**E1W1 (ETS-BaU + ESD-BaU + FA)**	**E1W2 (ETS-BaU + ESD-BaU)**
% change vs **E1W1 (ETS-BaU + ESD-BaU)**				
GDP	0.03%	-0.07%	0.05%	-1.04%
Gross Value Added				
Paper, pulp and print	0.18%	0.03%	0.14%	-0.98%
Non-Metallic Minerals	0.74%	1.50%	0.05%	6.00%
Non-ferrous metals	0.57%	1.99%	0.03%	4.57%
Motor vehicles	0.00%	-0.72%	0.09%	-5.91%

Chemistry	0.49%	1.56%	-0.09%	17.52%
Iron and Steel	1.98%	4.31%	3.08%	21.89%
Machinery	-0.06%	-0.62%	0.07%	-5.07%
Food and tobacco	-0.07%	-0.60%	-0.02%	-4.71%
Rest of Industry	0.05%	0.10%	0.15%	0.17%

Table 6 shows that for a higher ambition level inside of the EU-28, the free allowances have the potential to slightly increase the European GDP. Regarding the industrial sectors, their output is higher on the free allowance scenario in 2030, when there is a higher share of free allowances available. In 2050 there are fewer sectors positively influenced by the free allocation of allowances, which indicates that in the long term there should be different measure to boost competitiveness besides, solely, the free allocation.

Table 6: Results for REEEM Pathway with Free allowances vs without free allowances

Year	2030	2050
% change vs **E2W2 (ETS-80 + ESD-new)**		
GDP	0.03%	0.11%
Gross Value Added		
Paper, pulp and print	0.20%	0.35%
Non-Metallic Minerals	0.83%	-0.04%
Non-ferrous metals	0.63%	-0.07%
Motor vehicles	0.00%	0.24%
Chemistry	0.54%	-0.41%
Iron and Steel	2.14%	8.79%
Machinery	-0.07%	0.25%
Food and tobacco	-0.08%	-0.08%
Rest of Industry	0.06%	0.51%

These results suggest that the free allowance policy might be a small benefit for the European economy, as long as the burden it imposes to other sectors remains small. Additionally, higher emission cuts in the rest of the World benefits the energy intensive sectors more than the free allowance policy, but the costs that comes with it might influence negatively sectors that are responsible for a higher share of the European GDP, such as machinery and motor vehicles

5. Conclusion

The results shown in this work demonstrate how competitiveness of different industrial sectors are affected by emission targets within and outside the EU-28. Additionally, it presents two ways to mitigate the negative economic effects of reducing emission by means of electrification and by continuing allocating CO_2 allowances for free to specific sectors in the coming years.

First, it was presented a negative relationship between emission cuts in the EU-28 and its potential GDP growth in 2050. Higher emission reductions tend to increase the prices for ETS allowances, forcing industrial facilities to pay a higher price for its emissions or invest on new technologies. On either ways, there is an increase in the costs faced by those firms, which tends to decrease GDP growth in the long term. According to Figure 2, reducing emissions in the EU from the BaU trajectory (about 50% reduction in 2050 compared to 1990 levels) to 80% reduction in 2050, compared to 1990 levels, decreases the GDP growth potential from roughly 75% to around 50% higher than 2011 levels. Furthermore, increasing the reduction to 90%, decreases the GDP growth potential to a range between 30 and 40% higher than 2011 levels.

The results presented in Table 4 suggest that the upper limit for the share of emissions cut in the EU-28 that leak to other regions remains in a range between 25 and 39%, as they consider only the cases where there are no policies in the rest of the World limiting the GHG emissions. Additionally, the leakage to the BRICS countries was very low, as shown in Figure 5, and the single country to where the highest amount of emissions leaked to was the USA, because it competes with the EU-28 in several sectors and would, therefore, profit from higher costs imposed to the European sectors.

In terms of effects on industrial sectors, the energy intensive sectors are highly affected by higher emission cuts in the EU-28, mainly due to higher allowances costs, which increases the cost of energy. The policy portfolio plays an important role on the impact cause to the energy intensive sectors as by utilizing policy ETS-all-80%, where all sectors are included in the ETS and the CO_2 reduction target in 2050 is 80% of 1990 levels, benefits the GDP, compared to alternative policy measures with similar emission targets, but hurts the GVA of energy intensive sectors. At the same time, sectors which are not energy intensive have low or no impact from emission cuts in the EU.

As a form to alleviate the negative economic impacts of emission cuts, the results suggest that increasing the flexibility in which fossil fuels can be substituted by electricity do improve the overall economy performance, in the form of a higher GDP, when compared to scenarios with lower flexibility. Nevertheless, for the energy intensive sectors, this higher degree of flexibility is only beneficial when the EU-28 decides to pursue emission cuts higher than 80%.

When the rest of the World increases its emission cuts, there are two distinct effects within the EU-28. For the energy intensive sectors there is an increase in GVA, while for the remaining sectors it tends to decrease. The net effect for the European economy is a decrease in GDP, since the sectors of machinery and motor vehicles, who are not energy intensive and represent a high share of the total production in the EU, also face a decrease in GVA.

The free allocation of allowances, especially for the E2W2 scenario combination, causes a positive impact on both the GDP and GVA of energy intensive sectors in the short term (until 2030). For the long term, however, the effects for these sectors is rather mixed, as some still profit from it, such as paper, pulp and print and iron and steel. The latter with almost 9% increase in GVA. It is important to note, however, that the sectors which do not receive free allowances tend to underperform.

Finally, this analysis did not consider positive impacts from higher emission reduction targets, such as higher life quality due to lower pollution or faster technology development. These two aspects, however, have a great impact on how the industry and the entire economy will develop in the coming years, so it is expected that, when accounting it, the negative impacts of reducing emissions will likely be alleviated. Additionally, it was shown that the policy portfolio applied in the EU plays a determinant role not only in how the GDP develops, but also on industrial sectors. But most importantly, if the target is to keep competitiveness in energy intensive sectors high, having other developed nations to also follow high emission cuts has a higher positive impact than allocating allowances for free.

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Appendix

A.1 Carbon leakage

Table 7: Carbon leakage definitions

Carbon leakage definition	Source
Carbon leakage refers to the situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints. This could lead to an increase in their total emissions. The risk of carbon leakage may be higher in certain energy-intensive industries.	[2]
Carbon leakage can be defined as the ratio of emissions increase from a specific sector outside the country (as a result of a policy affecting that sector in the country) over the emission reductions in the sector (again, as a result of the environmental policy).	[28]
Carbon leakage is defined as the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries.	[29]
Carbon leakage can be defined as the displacement of economic activities and/or changes in investment patterns, that directly or indirectly cause GHG emissions to be displaced from a jurisdiction with GHG constraints to another jurisdiction, with no or less GHG constraints.	[30]
Carbon leakage is defined as the increase in emissions outside a region as a direct result of the policy to cap emission in this region.	[31]

A.2 Modeling framework

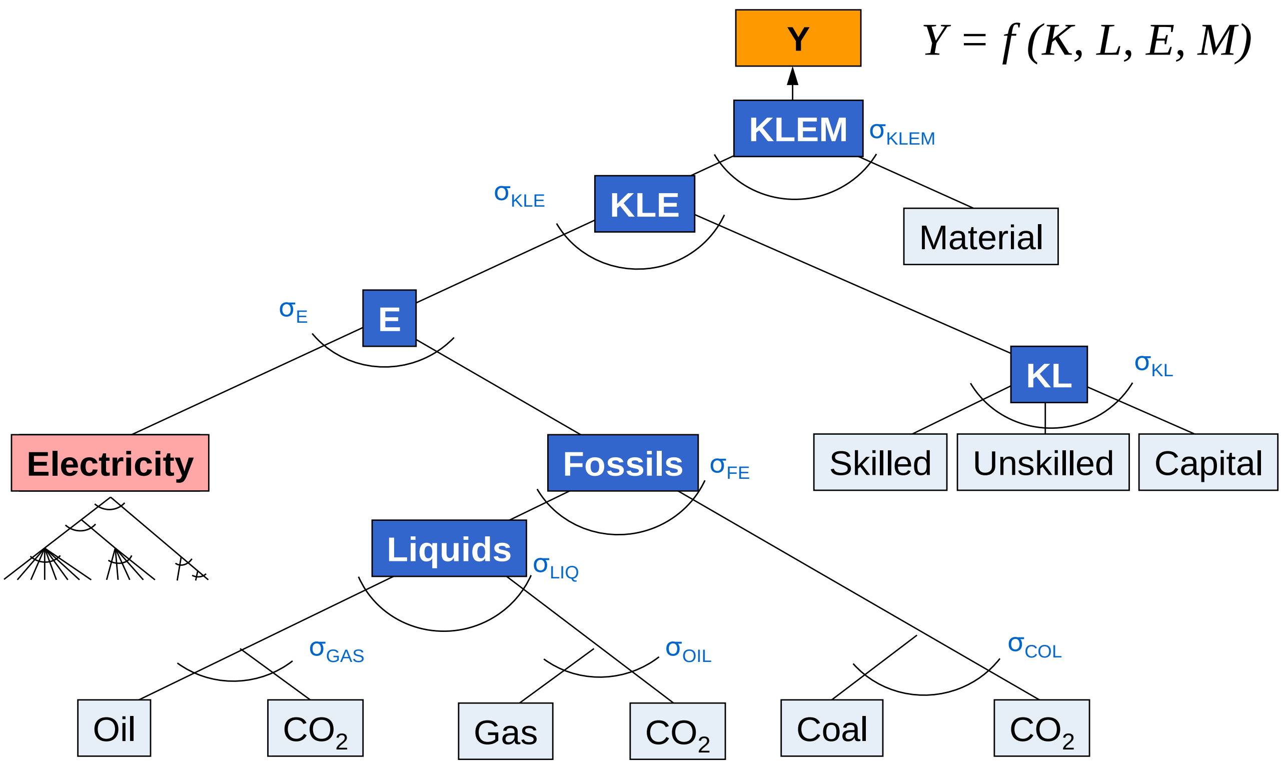

Figure 11: CES structure in NEWAGE for the production sectors

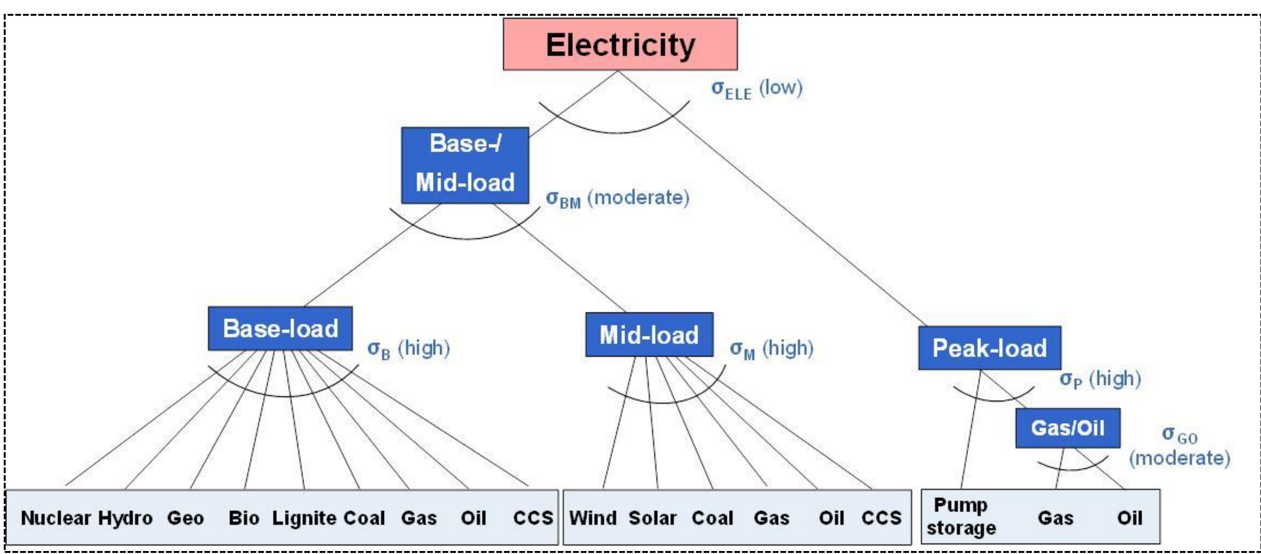

Figure 12: CES structure in NEWAGE for electricity production

Table 8: List of production sectors in NEWAGE

No.	Sector	Group
1	Coal	Energy production
2	Natural gas	Energy production
3	Crude oil	Energy production
4	Oil refining	Energy production
5	Electricity	Energy production
6	Iron & Steel	Energy intensive industries
7	Non-ferrous metals	Energy intensive industries
8	Non-metallic minerals	Energy intensive industries
9	Paper, pulp & print	Energy intensive industries
10	Chemicals	Energy intensive industries
11	Food & Tobacco	Energy intensive industries
12	Motor vehicles	Other manufacturing
13	Machinery	Other manufacturing
14	Rest of industry	Other manufacturing
15	Buildings	Rest of the economy
16	Transport	Rest of the economy
17	Agriculture	Rest of the economy
18	Services	Rest of the economy

Table 9: Technology portfolio available at the electricity sector of NEWAGE

No.	Load	Technology
1	Base	Nuclear
2	Base	Hydro
3	Peak	Hydro
4	Base	Geothermal
5	Medium	Solar
6	Medium	Wind
7	Base	Hard Coal
8	Medium	Hard Coal
9	Base	Brown Coal
10	Base	Oil
11	Medium	Oil
12	Peak	Oil
13	Base	Gas
14	Medium	Gas
15	Peak	Gas
16	Base	Biomass
17	Base	CCS
18	Medium	CCS

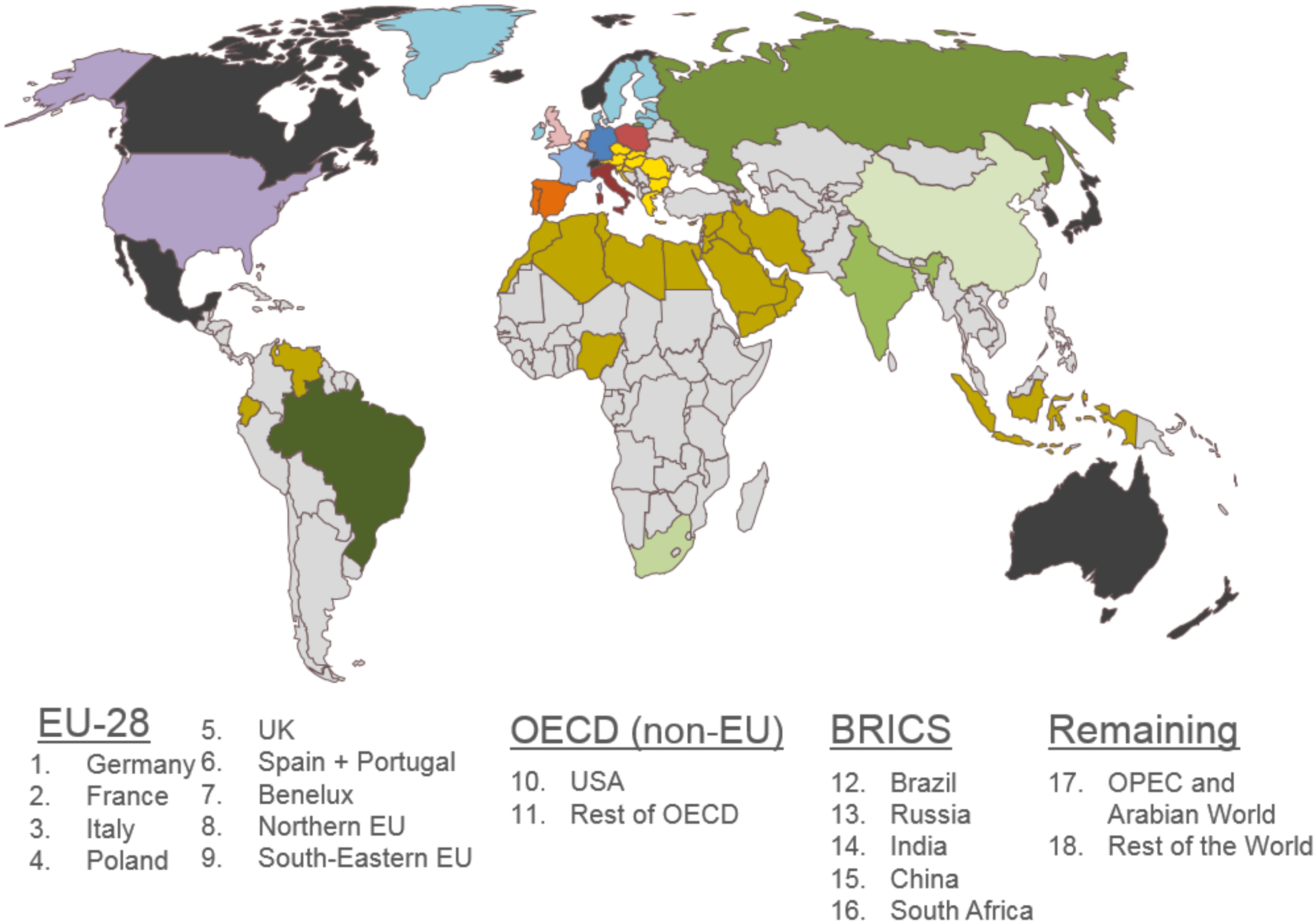

Figure 13: Regional disaggregation in NEWAGE. Each region in the model has its own color in the map

A.3 Assumptions

Table 10: Substitution elasticities in NEWAGE for consumption

CES parameter	Substitution elasticity between	Value
$\sigma^{C\text{-}ENE}$	energy and non-energy-goods aggregate	0,5
$\sigma^{C\text{-}NE}$	non-energy-goods	1
$\sigma^{C\text{-}E}$	energy carriers (electricity, gas, oil, coal)	1
$\sigma^{C\text{-}GAS}$	gas and CO_2 emissions	0
$\sigma^{C\text{-}OIL}$	oil and CO_2 emissions	0
$\sigma^{C\text{-}COL}$	coal and CO_2 emissions	0

Table 11: Substitution elasticities in NEWAGE for industry production

CES parameter	Substitution elasticity between	Value
σ^{KLEM}	material and capital-labor-energy	0
σ^{KLE}	Capital, labor and energy	0,5
σ^{KL}	capital, skilled and unskilled labor	1
$\sigma^{KL\text{-}refOil}$	capital, skilled and unskilled labor	0,2
σ^{LAB}	skilled and unskilled labor	0,5
σ^{E}	electricity and fossil fuels	0,1
σ^{FE}	Liquid and solid fossil fuels	0,5
σ^{LQD}	gas aggregate and oil aggregate	2
σ^{OIL}	oil and CO_2 emissions	0
σ^{COL}	coal and CO_2 emissions	0
σ^{GAS}	gas and CO_2 emissions	0

Table 12: Substitution elasticities in NEWAGE for electricity production

CES parameter	Substitution elasticity between	Value
σ^{ELE}	base-, mid- and peak-load	0,8
σ^{PL}	electricity generation technologies peak-load	5
σ^{OG}	Peak-load gas and oil turbines	2,5
$\sigma^{BM\text{-}EU}$	base- and mid-load for EU28 regions	5
$\sigma^{BM\text{-}RoW}$	base- and mid-load for non-EU28 regions	4
σ^{BL}	electricity generation technologies base-load	8
σ^{ML}	electricity generation technologies mid-load	5

Table 13: Substitution elasticities in NEWAGE for trade

CES parameter	Substitution elasticity between	Value
σ^{A}	Armington Elasticity (substitution between local production and imported goods)	4
σ^{IM}	imported goods from different countries	8
σ^{TS}	imported good and associated transport service	0

Table 14: Emission reduction targets for the REEEM pathway – in the EU

	Targets for 2020 (compared to 2005)	*Targets for 2030 (compared to 2005) - Proposal*	*Target for 2050 (compared to 2005) – E2: Cluster Union*
EU-28 ETS	-21%	-43%	-83%
	Effort sharing decision (ESD)	Effort sharing decision (ESD-new)	Effort sharing decision (ESD-new)
France	-14%	-37%	-80%
Portugal	1%	-17%	-80%
Spain	-10%	-26%	-80%
Italy	-13%	-33%	-80%
United Kingdom	-16%	-37%	-80%
Austria	-16%	-36%	-80%
Germany	-14%	-38%	-80%
Netherlands	-16%	-36%	-80%
Belgium	-15%	-35%	-80%
Luxembourg	-20%	-40%	-80%
Austria	-16%	-36%	-80%
Denmark	-20%	-39%	-80%
Sweden	-17%	-40%	-80%
Finland	-16%	-39%	-80%
Ireland	-20%	-30%	-80%
Poland	14%	-7%	-50%
Czech Republic	9%	-14%	-50%
Bulgaria	20%	0%	-60%
Romania	19%	-2%	-60%
Estonia	11%	-13%	-60%
Latvia	17%	-6%	-60%
Lithuania	15%	-9%	-60%
Croatia	11%	-7%	-60%
Hungary	10%	-7%	-60%
Greece	-4%	-16%	-60%
Slovakia	13%	-12%	-60%
Slovenia	4%	-15%	-60%
Cyprus	-5%	-24%	-60%
Malta	5%	-19%	-60%
EU-28	-9%	-30%	-75%

Regional Push

The Regional Push scenario can be translated as the mutual work of several regions that, together, concentrate at least half of the global emissions and have the economic means to pursue emission targets that are consistent with the 2 °C target[9], or at least more ambitious than the current policies[10].

Since the EU-28 has specific emission targets, Table 15 depicts only the emission targets of regions outside of the EU that pursue a higher emission cut than the current policies in the Regional Push World state.

Region	CO2 emission targets in 2050
USA	Halfway between 2 °C target and current policies
China	2 °C target
Japan	Halfway between 2 °C target and current policies
Republic of Korea	2 °C target
Canada	Halfway between 2 °C target and current policies
Mexico	Halfway between 2 °C target and current policies
Australia	Halfway between 2 °C target and current policies
Norway	80% reduction compared to 1990 levels
Switzerland	80% reduction compared to 1990 levels
New Zealand	2 °C target
Iceland	2 °C target

Table 15: Emission targets for regions outside of the EU-28 pursuing emission cuts higher than the current policies for the Regional Push World state

[9] According to the emission path presented in 2DS from [26]
[10] According to the emission path RTS from [26]

A.4. Free allocation of allowances - implementation

The analysis of the free allocation of allowances was a request from the stakeholders at the workshop "Macroeconomic projections for the European Union until 2050" held in Brussels in April 2018. Since most of the attendees were representatives from the energy intensive industries, this policy, and its maintenance, is of critical importance to them, as it aims on supporting the industrial facilities with higher risks of carbon leakage.

According to the European commissions [32], a sector or sub-sector is facing significant risk of carbon leakage if:

- direct and indirect costs induced by the implementation of the directive would increase production cost, calculated as a proportion of the gross value added, by at least 5%; and
- the sector's trade intensity with non-EU countries (imports and exports) is above 10%.

A sector or sub-sector is also deemed to be exposed if:

- the sum of direct and indirect additional costs is at least 30%; or
- the non-EU trade intensity is above 30%.

Two lists were created by the EC with the sectors and sub-sectors deemed to be exposed to a significant risk of carbon leakage. The first one[11] was applied in 2013 and 2014 and the second[12] is being applied for the years between 2015 and 2019.

The share of allowances being freely allocated depends of both the year and the sector. If the sector is exposed to a significant risk of carbon leakage, the installations contained in it are eligible to receive 100% of the allowances for free. For sectors not on the carbon leakage list, however, the free allocation reduces gradually from 80% in 2013 to 30% in 2020 [32]. Additionally, as part of the 2030 climate and energy policy framework, it was decided that the free allocation of allowances for sectors facing risk of carbon leakage would continue until 2030[13].

For this exercise, the implementation of the free allowances policy in NEWAGE was done in a two steps procedure. First, past data for the quantity of verified emissions and free allowances per sector and year were aggregated into the sectors contained in NEWAGE. This data is available in different websites with different degrees of aggregation [33] [34]. From this first stage it was possible to define the share of free allowances per sector for the year 2015. The second step consisted of doing a linear regression on of the share of free allowances per sector, using data from 2013 to 2017, until 2050. It is also important to emphasize that although the value of free allowances deviate from country to country, for this specific work it was adopted one European value that would subsequently applied in every EU-28 region

[11] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32010D0002&from=EN
[12] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32014D0746&from=EN
[13] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52014DC0015&from=EN

in NEWAGE. Figures 14 to 19 depict the historical and projected shares of free allowances for each sector in the model. For the years where the linear regression indicated a negative share, it will be considered a share of 0% instead.

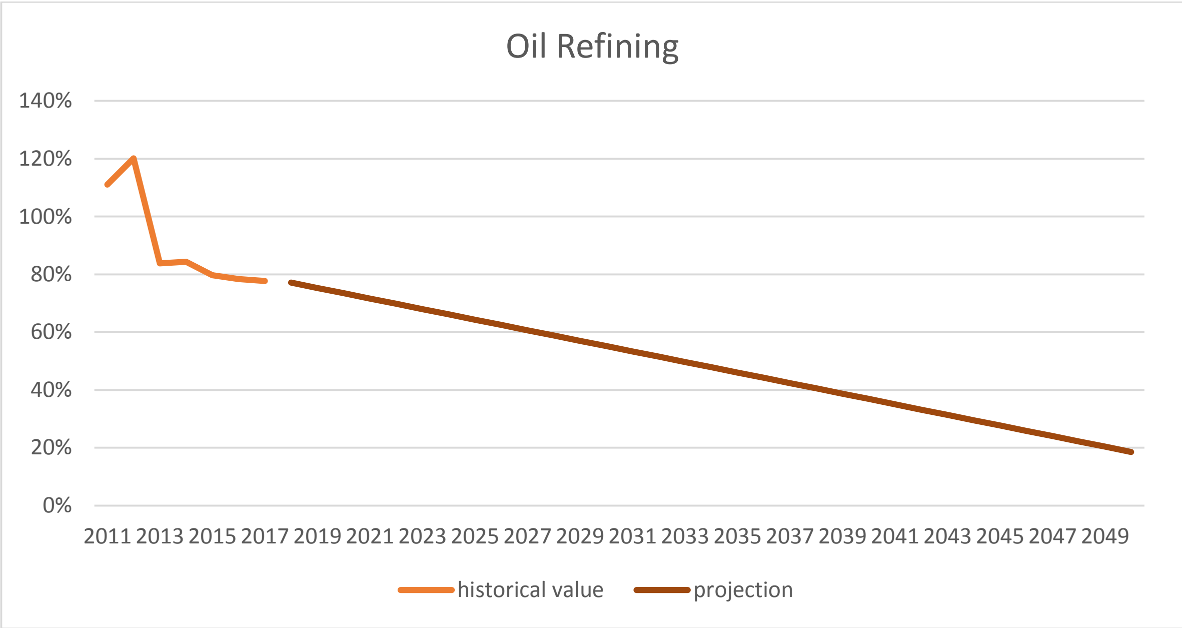

Figure 14: Historical and projected share of free allowances for the oil refining sector

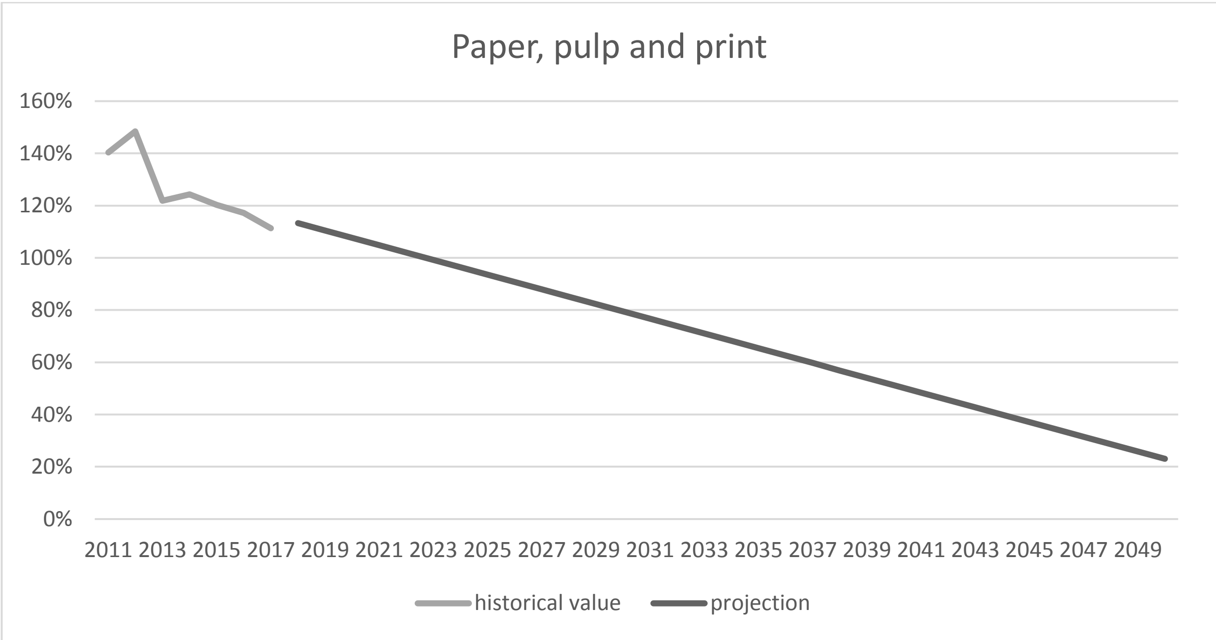

Figure 15: Historical and projected share of free allowances for the paper, pulp and print sector

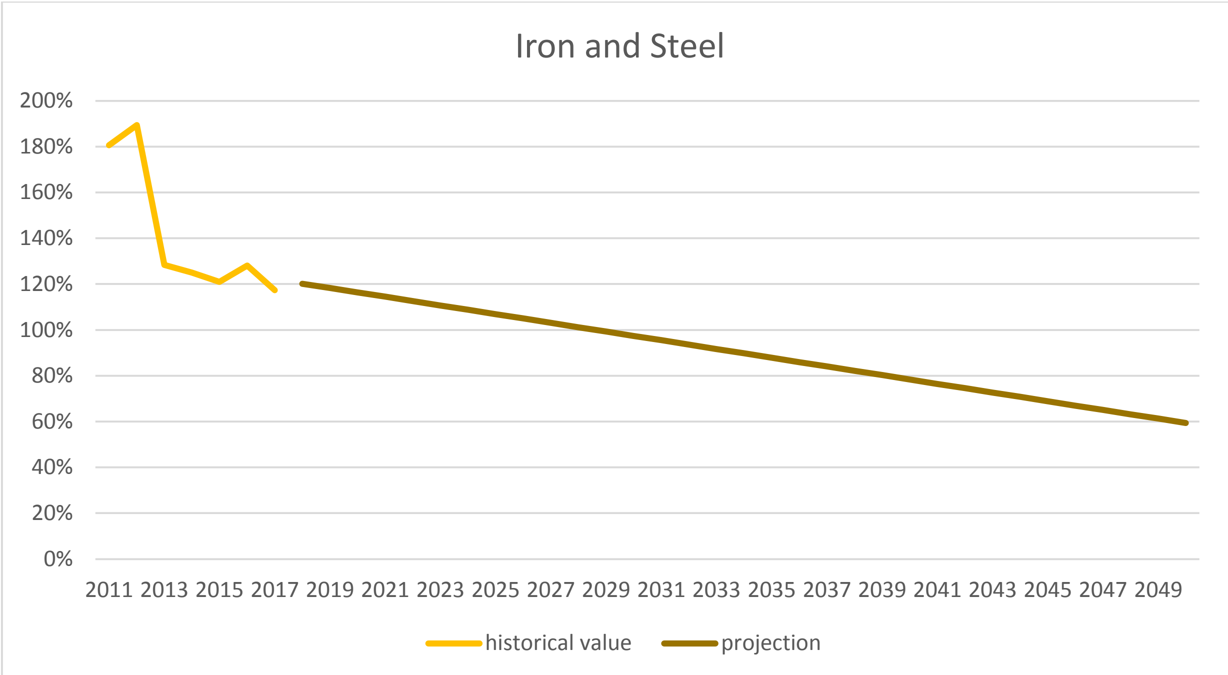

Figure 16: Historical and projected share of free allowances for the iron and steel sector

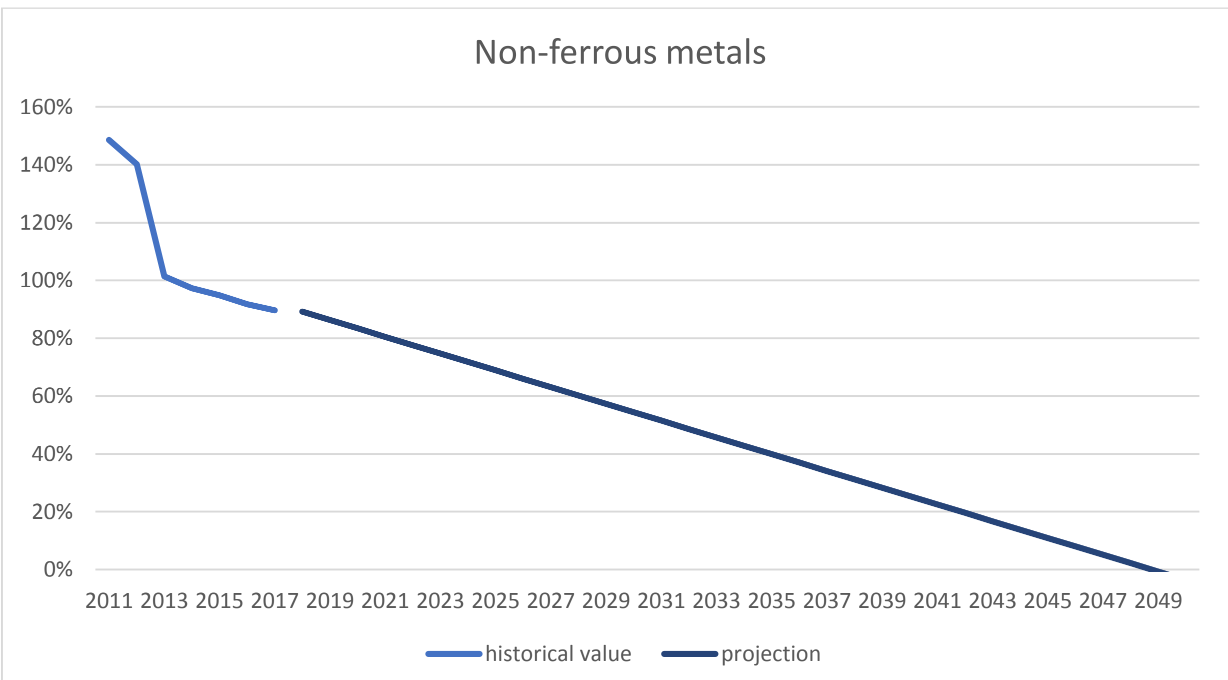

Figure 17: Historical and projected share of free allowances for the non-ferrous metals sector

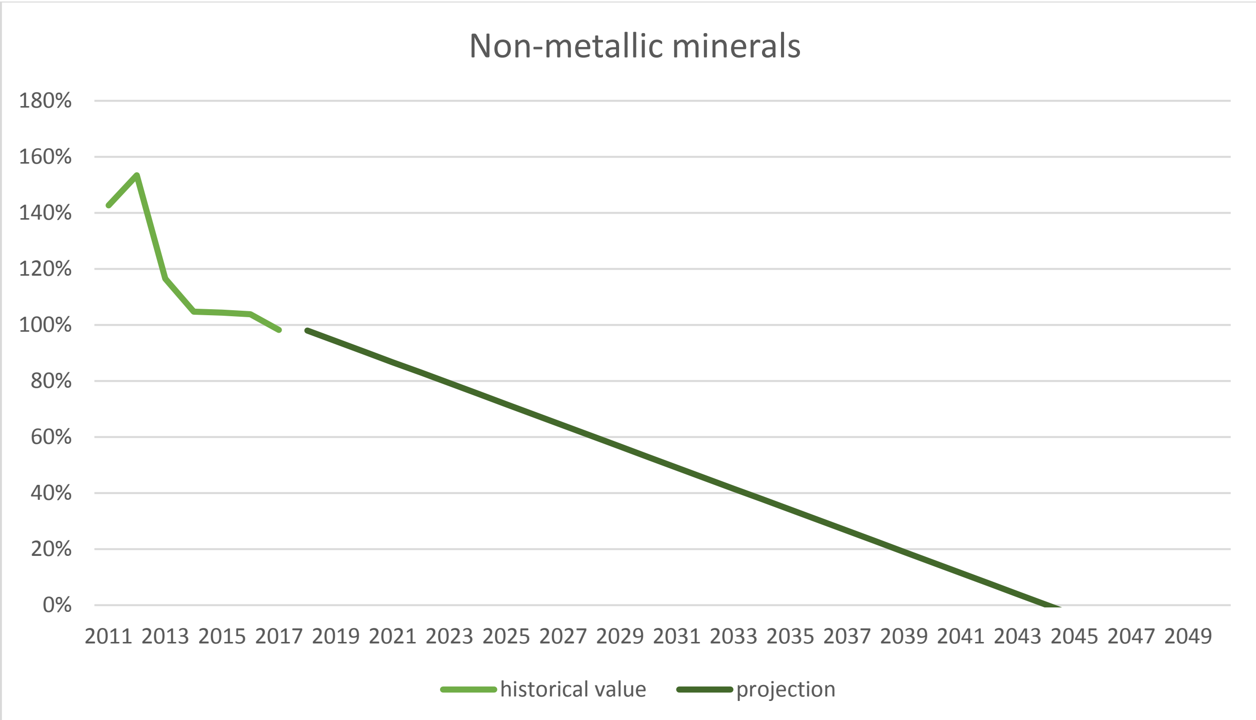

Figure 18: Historical and projected share of free allowances for the non-metallic minerals sector

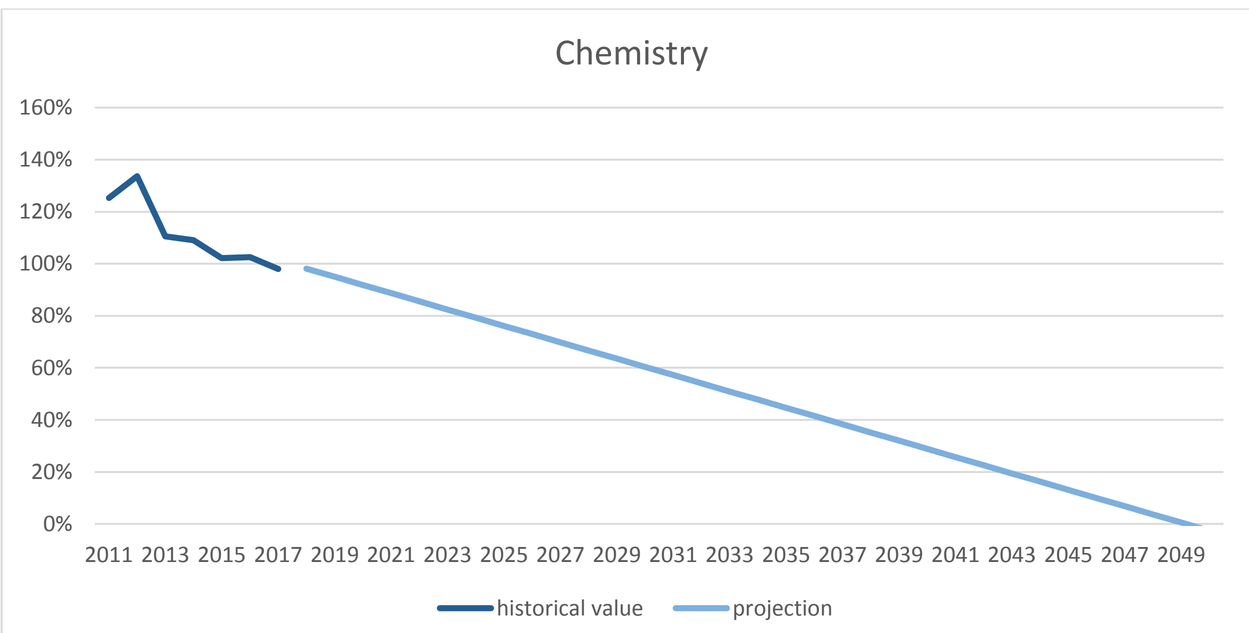

Figure 19: Historical and projected share of free allowances for the chemistry sector