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Emission pricing and CO_2 compensation in the EU

The optimal compensation to the power-intensive and trade-exposed industries for increased electricity prices

TALL SOM FORTELLER

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Abstract

Unilateral CO_2 emission reduction can lead to carbon leakage, such as relocation of power-intensive and trade-exposed industries. In the EU emission trading system, these industries are also subjected to higher cost of electricity due to emission pricing in this sector. As a result, the industries in the EU receive free emission allowances to mitigate carbon leakage as well as CO_2 compensation due to higher electricity cost. This paper examines the welfare effects of supplementing free allowances with a CO_2 compensation on the power-intensive and trade-exposed goods. The analytical results suggest that introducing CO_2 compensation has a regional and global welfare improving effect under certain plausible conditions. Numerical simulations in the context of the EU ETS support the analytical findings if the emission reduction target is stringent enough.

Keywords: CO_2 compensation; Emission trading system; Unilateral policy; Carbon leakage

JEL classification: D61; F18; H23; Q54

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Sammendrag

Regionale tiltak for å redusere klimagassutslipp kan føre til karbonlekkasje, som f.eks. flytting av kraftkrevende og handelsutsatt industri. I EUs kvotesystem er disse næringene også utsatt for høyere kostnader gjennom deres elektrisitetsbruk på grunn av utslippspriser i denne sektoren. Industrien mottar derfor gratiskvoter i EU for å unngå karbonlekkasje samt CO_2 kompensasjon på grunn av høyere strømkostnader. Denne artikkelen undersøker velferdseffektene av å supplere gratis utslippskvoter med CO_2 kompensasjon til den kraftkrevende og handelsutsatte industrien. De analytiske resultatene tyder på at innføring av CO_2 kompensasjon vil ha en regional og global velferdsforbedrende effekt under visse akseptable betingelser. De numeriske simuleringene i sammenheng med EUs kvotesystem støtter de analytiske funnene dersom utslippsreduksjonsmålet er strengt nok.

1. Introduction

The European Union (EU) countries have among the worlds' most ambitious policies aimed at reducing greenhouse gas emissions (GHG). The EU 2030 climate and energy framework (EC-European Commission, 2021a) includes targets for GHG emissions for sources covered by the Emission Trading System (ETS) as well as for those outside of the ETS (Non-ETS). The EU must limit its emissions by 2030 with 55 per cent compared to its 1990 level.

Leakage can occur through the fossil fuel market, where reduced fuel demand in the emission regulating regions leads to lower international fuel prices. This will increase the fuel consumption and emissions in the unregulated regions. In addition, leakage can occur from the negative impact on the competitiveness of the emission-intensive and trade-exposed industries (EITE) sectors (e.g. steel, cement and chemical sectors). Emission regulations can affect industries to reduce production as the emission price increases their production cost. If this leads to lower profitability, this could cause carbon leakage by shifting production to countries where regulations are less stringent, and energy efficiency might be lower. This is particularly a concern for the EITE sectors. As a result, the policymakers in the EU ETS may achieve lower emission level locally, but risks losing jobs and industry to other regions, as well as higher GHG emissions abroad (Felder and Rutherford, 1993; Kaushal and Rosendahl, 2020). The carbon leakage is typically in the range of 5–30 per cent, cf. Zhang (2012) and Böhringer et al. (2012). There are, however, a few outliers with leakage rates above 100 per cent (Babiker, 2005). Studies that estimate leakage from EITE industries often find higher leakage rates (e.g., Ponssard and Walker, 2008; Fischer and Fox, 2012; and Kaushal and Rosendahl, 2021) since competitiveness losses for this sector get more pronounced.

Hence, policymakers have typically either exempted EITE industries from their climate regulation or implemented anti-leakage measures. For instance, sectors that are regulated by the EU ETS and "exposed to a significant risk of carbon leakage", are given a large number of free emission allowances (Böhringer et al., 2017; Kaushal and Rosendahl, 2020). The allocation is based on product-specific benchmarks to maintain incentives to reduce emissions per output unit. Further, the allocation is based on measurement of activity level and production volumes, to reduce leakage and limit surplus allowances (Neuhoff et al., 2016). Free allowance allocation conditional on output is often referred to as output-based allocation (OBA) (Böhringer and Lange, 2005). Further, the allocation of free allowances is subject to strict measurement of emission intensities, to ensure that output and not emissions is the basis for allocations. Similar allocation rules can be found in other carbon markets such as in New Zealand, California and the Chinese regional pilot schemes (World Bank, 2014; Xiong et al., 2017).

Free allowances can mitigate carbon leakage. However, this implicit output subsidy ends up stimulating domestic production and thereby resulting in too much consumption of these products globally (Böhringer and Lange, 2005). Hence, the incentives to substitute from carbon-intensive to carbon-free products are reduced. Further, as there is uncertainty about leakage exposure for individual sectors, policymakers may be persuaded to allocate too many permits to too many industries (Martin et al., 2014). In the EU there is a combination of free allocation methods and auctions.

Another anti-leakage measure is the indirect cost compensation for higher electricity costs. This is distributed to the power-intensive and trade-exposed industries (PITE), and not all EITE industries in general (see Appendix A for a list of PITE industries that receive compensation in addition to free allowances). Within the ETS, the industry must buy emission allowances for their own emissions. The outlay for these allowances is specified as direct costs of emissions for the PITE producer. Electricity producers also buy allowances for their emissions that further affect the price of electricity through higher production cost. Then, when PITE producers use electricity, they pay for these emissions through higher electricity prices. We refer to the latter as the indirect cost of emissions for the PITE producer. This may cause carbon leakage by shifting production to countries where electricity producers pay less for their emissions (Böhringer et al., 2015). Hence, following the same argument as with free allowances, to reduce carbon leakage the PITE sectors are compensated for the increase in electricity price that is caused by the EU ETS. While both OBA and CO_2 compensation are associated with the allowance price, the compensation is connected to electricity input in production and OBA to the production itself, and thus, the effects of the two instruments will most likely be different.

While the share of free allowances for the PITE sectors has declined since 2013, it still constitutes 94 per cent of the emissions in 2021 (Pellerin-Carlin, 2022). Moreover, the EU has expressed that they will continue with free allowances to these industries to combat carbon leakage.

The EU allows the indirect cost compensation under approved State Aid measures, but it is up to member states to choose whether to do so (EC- European Commission, 2021b). The EU Commission must approve the national schemes to ensure that they are in line with the EU state aid rules. The aid intensity must not exceed 75 per cent of the eligible costs incurred. Further, compensation is a function of electricity use as input in production, but electricity efficiency and emission coefficient benchmarks apply to ensure that compensation does not increase with low productivity (see EC- European Commission, 2021b for details). The magnitude of the allowed future compensation to the PITE industries is uncertain. Like free allowances, we emphasise that the compensation scheme might mitigate carbon leakage, but this implicit subsidy also ends up stimulating domestic carbon-intensive production.

Besides free allowances and compensation, policy responses to mitigate carbon leakage include a Carbon Border Adjustment Mechanism (CBAM). In a CBAM system EU importers will buy carbon certificates corresponding to the carbon price that would have been paid, had the goods been produced under the EU's carbon pricing rules. The EU has decided to start introducing a CBAM scheme gradually as from 2026 at the earliest. However, there is still great uncertainty about how the system of CBAM finally will be designed. Nevertheless, existing instruments of free allowances and the indirect compensation for increased costs due to higher electricity prices that are designed to dampen carbon leakage are intended to be prolonged at least to 2026 and may co-exist with CBAM in one form or another until 2035.

Both free allowances through OBA and compensation stimulate PITE production. Is this a sensible combination of measures to combat carbon leakage, or is it overstimulating the production of PITE industries? Thus, our research question is to find the optimal level of compensation when there already is OBA in place. We look for the optimal level in terms of regional and global welfare (see e.g. Böhringer et al., 2017; Kaushal and Rosendahl, 2020). We also study the effect on carbon leakage rates and emissions. We emphasise that if the scenarios have less than 100 per cent free allowances, the remaining quotas are auctioned (and revenue is recycled).

When we search for the optimal compensation level that maximises welfare, we will already now point out that the stringency of the emission target in the EU is crucial. There are two important opposite effects on regional welfare coming from changes in the leakage rate and changes in terms of trade. However, a more stringent emission cap leads to higher optimal compensation because the positive effect of reduced leakage outweighs the negative terms of trade effect.

Particularly, the economic instruments of OBA/free allowances have been investigated by a strand of economic literature. Many of these studies look at optimal OBA and free allowances under various conditions. Jensen and Rasmussen (2000) compare three allocation methods which is auctioning, grandfathering and OBA, based on market share in emissions trading in Denmark. Böhringer and Lange (2005) analyse the effects of emissions trading in the EU (primarily Germany), under auctioning, OBA, and free allocation based on emissions volume (i.e., share of emissions). Dissou (2006) employs a forward-looking dynamic computable general equilibrium (CGE) model to analyse emissions trading in Canada under auctioning, grandfathering and OBA. Fischer and Fox (2007) employ a CGE model for a quantitative analysis of the three methods: auctioning, grandfathering and OBA in the US. Fischer and Fox (2010) extend this work by looking at specific combinations of OBA with either auctioning or grandfathering. They show that combining auctioning with OBA for energy intensive sectors is more cost-effective policy than auctioning alone. Takeda et al. (2014) build on the model of Fischer and Fox (2010) and compare auction schemes, grandfathering schemes and OBA schemes for the Japanese economy. Kaushal (2020) finds that OBA in the presence of other regulated regions may be beneficial if the regulated regions want to maintain their world market share of PITE goods. Moreover, OBA seems to have a strong carbon leakage mitigation effect. Of the above-mentioned studies only Fischer and Fox (2010) look at how stringency of the emission target may affect the welfare impact of OBA/free allowances (that internalizes the change in leakage rate by achieving the constant global emission reduction). Similar to our results, they show larger welfare improvement from OBA with more stringent emissions targets.

We have only found one analysis, Ferrara and Giua (2022), that studies indirect compensation. However, they conduct an ex-post analysis and focus on the effects at the firm level. Hence, we have not found any studies that look at a situation where the PITE sectors receive compensation for higher electricity prices as well as free allowances. To study optimal compensation in the presence of OBA, we first develop a theoretical model. To test the outcomes from our theoretical model, we also develop a detailed numerical simulation model for the quantitative analysis to get more in-depth insights into the proportion of economic effects based on empirical data.

Section 2 describes the theoretical model. In Section 3 we look at the numerical results and Section 4 concludes.

2. Theoretical model

Consider two regions denoted r, one domestic (D) and one foreign (F), $r = (D, F)$. We have furthermore three goods in the regions x, y, z. Good x is emission-intensive and non-tradable (e.g., electricity or transport), y is power-intensive and trade-exposed (PITE) (e.g., chemicals, metals and other minerals), and z is emission-free and tradable. The goods are produced in the two regions and we here assume that same types of goods are homogeneous with no cost related to trade (for y and z).[1] The relocation of production of the y good may occur due to trade exposure, and thus OBA and CO_2 compensation are considered for this sector. The market price for the goods in region r, are denoted p^{xr}, p^{yr} and p^{zr}.

Now, assume that the domestic region D implements an emission trading system, regulating emissions from production of the goods x and y:

$$\bar{\bar{E}}^D = e^{xD} + e^{yD}. \tag{1}$$

e^{xr} and e^{yr} is the emission from goods x and y in region r. $\bar{\bar{E}}^D$ is the binding cap on total emission in region D, and the emission price t^D is determined through the emission trading system. We assume that the emission price in region D is positive and zero in region F, i.e., $t^D > 0$ and $t^F = 0$ as there is no climate regulation in region F.

Region D has initially implemented OBA to mitigate carbon leakage to region F. With OBA, the producers of good y receives free emission allowances in proportion to their output. We let o^D denote OBA to production of good y in the regulating region D. Region D determines the OBA with a share α^D, such that $o^D = \alpha^D t^D \left({e^{yD}}/{y^D} \right)$. α^D varies between 0 and 1, with α^D set to 1 if the emission price is fully rebated. There is no OBA to producers of the non-trade-exposed good x.

Region D also implements the CO_2 compensation on top of the OBA to protect PITE producer y from the increased electricity prices. We denote the CO_2 compensation in region D by μ^D. The producer receives a compensation, μ^D, in proportion to its use of electricity in the regulating region D, $\tilde{x}^D$. Alternatively, we can implement it as an output subsidy, but in this case, it is implemented in the same way as the OBA.

In each region r we assume a representative household with utility given by $u^r(\bar{x}^r, \bar{y}^r, \bar{z}^r)$. The bar indicates demand of the three goods by the household. Further, the utility function is assumed twice

[1] In the numerical simulation we mainly assume the case of heterogeneous/Armington goods.

differentiable, increasing and strictly concave. That is, the Hessian matrix is negative definite, and we have a local maximum, i.e., it follows the normal assumptions.

The production of good y in region r is denoted as $y^r = y^{rD} + y^{rF}$, where y^{rj} is produced goods in region r and sold in region $j = (D, F)$, and similarly for the emission free and tradable good z. The cost of production for each good in region r, excluding purchase of electricity and emission allowances, are given by the cost functions $c^{xr}(x^r, e^{xr})$, $c^{yr}(y^r, e^{yr}, \tilde{x}^r)$ and $c^{zr}(z^r)$. The cost functions of production are assumed to be increasing in output, c_x^{xr}, c_y^{yr}, $c_z^{zr} > 0$ (where $\frac{\partial c^{xr}}{\partial x^r} \equiv c_x^{xr}$, $\frac{\partial c^{yr}}{\partial y^r} \equiv c_y^{yr}$ and $\frac{\partial c^{zr}}{\partial z^r} \equiv c_z^{zr}$) and decreasing function of both emissions and electricity,[2] with strict inequality when emission is regulated ($c_{\tilde{x}}^{yr} < 0$; c_e^{xr}, $c_e^{yr} \leq 0$). The cost functions are twice differentiable, strictly convex and all derivatives are assumed to be finite. Finally, we assume that the marginal cost of production for producer of good y – excluding the purchase cost of electricity and emission allowances – increases if either electricity or emissions decline. Note that power-intensive industries use of electricity is closely linked to the process emissions at the production plant. Hence, emission and electricity are assumed complementary inputs for producer of good y.[3]

The supply and demand in each region give us the following market equilibrium conditions:

$$
\begin{aligned}
x^r &= \bar{x}^r + \tilde{x}^r \\
y^D + y^F &= \bar{y}^D + \bar{y}^F \\
z^D + z^F &= \bar{z}^D + \bar{z}^F.
\end{aligned}
\tag{2}
$$

The competitive producers in region $r = D, F$ maximize profits π^r such that:[4]

$$
\begin{aligned}
Max_{x^r, e^{xr}}\ \pi_x^r &= [p^{xr}x^r - c^{xr}(x^r, e^{xr}) - t^r e^{xr}] \\
Max_{y^{rj}, e^{yr}, \tilde{x}^r}\ \pi_y^r &= \sum_{r=D,F} [(p^{yj} + o^r)y^{rj}] - c^{yr}(y^r, e^{yr}, \tilde{x}^r) - (p^{xr} - \mu^r)\tilde{x}^r - t^r e^{yr} \\
Max_{z^r}\ \pi_z^r &= \sum_{r=D,F} [p^{zj}z^{rj}] - c^{zr}(z^r)
\end{aligned}
\tag{3}
$$

Since region F does not undertake any environmental policy, we have that $t^F = o^F = \mu^F = 0$ (see above). Assuming interior solution, we have the following first order conditions for producer y:

[2] This simply means that it is costly to reduce emissions or electricity in production.
[3] We assume that the cross-derivates are negative, similar e.g., Böhringer and Rosendahl (2022).
[4] To simplify notation, we replace $\sum_{j=D}^{F} x^{rj}$ with x^r in the equations.

$$\frac{\partial \pi_y^D}{\partial y^D} = p^{yD} + o^D - c_y^{yD} = 0; \quad \frac{\partial \pi_y^F}{\partial y^F} = p^{yF} - c_y^{yF} = 0$$

$$\frac{\partial \pi_y^D}{\partial e^{yD}} = -c_e^{yD} - t^D = 0; \quad \frac{\partial \pi_y^F}{\partial e^{yF}} = -c_e^{yF} = 0 \tag{4}$$

$$\frac{\partial \pi_y^D}{\partial \tilde{x}^D} = -c_{\tilde{x}}^{yD} - (p^{xD} - \mu^D) = 0; \quad \frac{\partial \pi_y^F}{\partial \tilde{x}^F} = -c_{\tilde{x}}^{yF} - p^{xF} = 0$$

and the first order conditions for producer x and z:

$$\frac{\partial \pi_x^r}{\partial x^r} = p^{xr} - c_x^{xr} = 0$$

$$\frac{\partial \pi_z^D}{\partial z^D} = p^{zD} - c_z^{zD} = 0; \quad \frac{\partial \pi_z^F}{\partial z^F} = p^{zF} - c_z^{zF} = 0 \tag{5}$$

$$\frac{\partial \pi_x^D}{\partial e^{xD}} = -c_e^{xD} - t^D = 0; \quad \frac{\partial \pi_x^F}{\partial e^{xF}} = -c_e^{xF} = 0$$

The first line in Equation (4), and the first and second line in Equation (5) are the standard first order conditions. That is, the price of the good is equal to the marginal cost of producing that same good. Note that the optimal production of good y in region *D* ensures that the marginal cost of production is equal to the price for good y plus o^D. The second line in Equation (4) and third line in Equation (5) is the marginal cost of abatement, which is equal to the emission price for producer x and y in region r. The latter shows that the marginal abatement cost of emission is (as expected) equal to zero for the non-regulated region F. The last line in Equation (4) is the standard first-order condition for choice of input of electricity in production. The optimal choice in region *D* ensures that the producer receives the CO_2 compensation for each unit of electricity purchased. With the two tradable goods y and z the interior solution requires that the prices of the goods are equalized across regions, as they are homogeneous with no cost of trade. We may define this as:

$$p^y \equiv p^{yr}, \qquad p^z \equiv p^{zr}$$

The representative household in region r maximizes the net surplus π_u^D given consumption prices:

$$\pi_u^D = u^r(\bar{x}^r, \bar{y}^r, \bar{z}^r) - p^x \bar{x}^r - p^y \bar{y}^r - p^z \bar{z}^r \tag{6}$$

The first order conditions for the household is then (assuming interior solution):

$$\frac{\partial \pi_u^D}{\partial \bar{x}^r} = u_{\bar{x}^r}^r - p^x = 0, \qquad \frac{\partial \pi_u^D}{\partial \bar{y}^r} = u_{\bar{y}^r}^r - p^y = 0, \qquad \frac{\partial \pi_u^D}{\partial \bar{z}^r} = u_{\bar{z}^r}^r - p^{zr} = 0 \tag{7}$$

Finally, we assume that the regions have a balance-of-payment constraint. The net export from a region is equal to domestic production minus domestic consumption:

$$p^y(y^r - \bar{y}^r) + p^z(z^r - \bar{z}^r) = 0 \tag{8}$$

2.1. The optimal CO_2 compensation in region D under OBA

Regional welfare maximization

With these assumptions we can now specify the regional welfare W^r function to evaluate the different climate policies. The welfare in region *D* can be expressed by the sum of household surplus, producer surplus, government net revenues from sales of emission allowances and the cost of emission:

$$W^D = \pi_u^D + \pi_x^D + \pi_y^D + \pi_z^D + t^D \bar{\bar{E}}^D - o^D y^D - \mu^D \tilde{x}^D - \tau^D[e^{xD} + e^{yD} + e^{xF} + e^{yF}]$$

$$\begin{aligned} &= [u^D(\bar{x}^D, \bar{y}^D, \bar{z}^D) - p^x \bar{x}^D - p^y \bar{y}^D - p^z \bar{z}^D] + [p^{xD} x^D - c^{xD}(x^D, e^{xD}) - t^D e^{xD}] \\ &\quad + [(p^y + o^D) y^D - c^{yD}(y^D, e^{yD}, \tilde{x}^D) - (p^{xD} - \mu^D)\tilde{x}^D - t^D e^{yD}] + [p^z z^D - c^{zD}(z^D)] + t^D \bar{\bar{E}}^D \\ &\quad - o^D y^D - \mu^D \tilde{x}^D - \tau^D[e^{xD} + e^{yD} + e^{xF} + e^{yF}] \end{aligned}$$

where τ^D is region *D*'s valuation of reduced global GHG emissions.[5] The welfare function can be simplified to:

$$W^D = u^D(\bar{x}^D, \bar{y}^D, \bar{z}^D) - c^{xD}(x^D, e^{xD}) - c^{yD}(y^D, e^{yD}, \tilde{x}^D) - c^{zD}(z^D) - \tau^D[e^{xD} + e^{yD} + e^{xF} + e^{yF}] \tag{9}$$

By differentiating the regional welfare function w.r.t. the CO_2 compensation μ^D (see Appendix B), we arrive at the following result:

Lemma 1 *Let regional welfare be given by Equation (9), and assume that region D has implemented an emission trading system with emission price t^D and an output-based allocation o^D to the producer of PITE good y. Then, the regional maximizing welfare of the CO_2 compensation μ^{D^*} is given by:*

[5] Note that the permit price t^D might vary from τ^D.

$$\mu^{D*} = \frac{\left[-o^D \frac{\partial y^D}{\partial \mu^D} + \frac{\partial p^y}{\partial \mu^D}(y^D - \bar{y}^D) + \frac{\partial p^z}{\partial \mu^D}(z^D - \bar{z}^D) - \tau^D \left(\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right)\right]}{\frac{\partial \tilde{x}^D}{\partial \mu^D}} \tag{10}$$

Proof. See Appendix B.

The term in the denominator $\left(\frac{\partial \tilde{x}^D}{\partial \mu^D}\right)$ is positive since increasing the CO_2 compensation will reduce the electricity cost for producer of the good y (PITE good), leading to an increase in production of good y as cost of production decreases and then to the larger demand of the good x (electricity). By this assumption, the first term in the nominator is positive as well $\left(o^D \frac{\partial y^D}{\partial \mu^D}\right)$, since a CO_2 compensation imposed in region *D* reduces the cost of electricity for the PITE producer and hence increase the production of y^D. With a negative sign in front and $o^D > 0$, the first term $o^D \frac{\partial y^D}{\partial \mu^D}$ becomes negative. This term captures the negative effect of OBA which is strengthened with another implicit subsidy, the CO_2 compensation. The mechanism is basically the same as a so-called tax interaction effect, but in this case, the existing implicit production subsidy (OBA) makes the distortion of the CO_2 compensation (or subsidy) larger.[6]

The sum of the second and third terms in the nominator $\left(\frac{\partial p^y}{\partial \mu^D}(y^D - \bar{y}^D) + \frac{\partial p^z}{\partial \mu^D}(z^D - \bar{z}^D)\right)$ captures the terms-of trade effects for region *D*. As the supply of y^D increases with μ^D, p^y decreases i.e., $\frac{\partial p^y}{\partial \mu^D} < 0$. The household in both regions now demands more of the relatively cheaper good y, indicating that $\frac{\partial p^z}{\partial \mu^D}$ may decrease. Thus, whether the sum of the terms is positive or negative further depends on the effect of $\frac{\partial p^z}{\partial \mu^D}$, $(y^D - \bar{y}^D)$ and $(z^D - \bar{z}^D)$. If region *D* is net-importer of the good y, $\left[\left(\frac{\partial p^y}{\partial \mu^D}(y^D - \bar{y}^D) > 0\right)\right]$, and thus net exporter of good z, $\left[\left(\frac{\partial p^z}{\partial \mu^D}(z^D - \bar{z}^D) < 0\right)\right]$, then the sum of the terms is positive if the latter part is zero or $\left[\frac{\partial p^y}{\partial \mu^D}(y^D - \bar{y}^D) > -\frac{\partial p^z}{\partial \mu^D}(z^D - \bar{z}^D)\right]$. The intuition is that the compensation lowers the price of the imported good, which is welfare improving. If region *D* is net-importer of good z instead, then the term is positive if $\left[-\frac{\partial p^y}{\partial \mu^D}(y^D - \bar{y}^D) < \frac{\partial p^z}{\partial \mu^D}(z^D - \bar{z}^D)\right]$. Otherwise, the third term is ambiguous. It is, however, likely that the second term is greater than the third term since the compensation first affects the producer of the y good.

[6] The cost of the tax is larger with the existing taxes, which is known as tax interaction effect in the literature (e.g., Goulder, 1995).

The last term captures the emission effect in the unregulated region *F*. As the market price of good y falls, the supply of good y from region *F* - as well as emission related to producing – also decreases. Since the non-tradable good x is an input in production of good y, the production and emissions of producers of good x in region *F* decrease as well. Thus, the last term is negative. That is, the emission in the unregulated region *F* declines (i.e., leakage is reduced), $\left(\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right) < 0$. With a negative sign in front, the last terms become positive.

The optimal level of CO_2 compensation is in general ambiguous as there is one positive, one negative and one ambiguous term in the numerator. However, if the positive effect of the foreign emissions reduction is stronger than the sum of both strengthening effect of negative distortion of the OBA and the terms-of-trade effect (that can be negative), then the optimal CO_2 compensation in region *D* is positive.

Proposition 1

Consider a region r that has an emission trading system, where producers of the PITE goods, y, receives an Output-Based-Allocation. Then it is welfare improving for the region to also impose a CO_2 compensation on the electricity demand for the producer of the PITE good if the positive effect of reduced foreign emission is stronger than the sum of both the negative distortive side effect that strengthens the initial Output-Based-Allocation and the terms-of-trade effect.

Proof. The proposition follows from Lemma 1, and the discussion of the sign of Equation (10) above.

Global welfare maximization

Region *D* could be concerned about the global welfare when imposing the CO_2 compensation. The global welfare function is expressed as follows:

$$W^G = \sum_{r=D,F} \left[\pi_u^r + \pi_x^r + \pi_y^r + \pi_z^r + t^D \bar{\bar{E}}^D - o^D y^D - \mu^D \tilde{z}^D - \tau^D (e^{xr} + e^{yr})\right]$$

and can be further simplified to:

$$W^G = \sum_{r=D,F} [u^r(\bar{x}^r, \bar{y}^r, \bar{z}^r) - c^{xr}(x^r, e^{xr}) - c^{yr}(y^r, e^{yr}, \tilde{x}^r) - c^{zr}(z^r) - \tau^D (e^{xr} + e^{yr})] \tag{11}$$

Lemma 2 *Let the global welfare be given by Equation (11), and assume that region D has implemented an emission trading system with emission price* t^D *and Output-Based Allocation* o^D *to good y. Then the global maximizing welfare of the* CO_2 *compensation* μ^{D^*} *is given by:*

$$\mu^{D^{G*}} = \frac{\left[-o^D \frac{\partial y^D}{\partial \mu^D} - \tau^D \left(\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right)\right]}{\frac{\partial \tilde{x}^D}{\partial \mu^D}} \tag{12}$$

Proof. See Appendix C.

We know that $\left(\frac{\partial \tilde{x}^D}{\partial \mu^D}\right)^{-1}$ is positive, as CO_2 compensation increases the demand of electricity in region D. The increased demand leads to increased production of good y in region D, meaning that the next term $\left(o^D \frac{\partial y^D}{\partial \mu^D}\right)$ is still positive, however with a negative sign in front. From our previous discussion we argue that the last term $\left(\tau^D \left(\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right)\right)$ is negative.

Region *D* was previously concerned about the terms-of-trade effect when considering the regional welfare. Equation (12) suggests that this is no longer the case if one is concerned about the global welfare effect of the CO_2 compensation, because the terms-of-trade effect is cancelled out for domestic and foreign regions. Thus, we see that from a global welfare perspective, the optimal CO_2 compensation in region D in the presence of an existing OBA in the same region can be stated with the following proposition:

Proposition 2 *Consider a region* r *that has an emission trading system, where producers of PITE goods,* y*, receive Output-Based-Allocation. Then it is global welfare improving that region* r *also imposes a* CO_2 *compensation on the electricity demand for the PITE producer if the positive effect of reduced global emission is stronger than the negative distortive side effect of the Output-Based-Allocation.*

Proof. The proposition follows directly from Equation (12).

Finally, consider the special case without OBA in region D. Equation (12) then becomes:

$$\mu^{D^{G*}} = \frac{-\tau^D \left(\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right)}{\frac{\partial \tilde{x}^D}{\partial \mu^D}} \tag{13}$$

We know that $\left(\frac{\partial \tilde{x}^D}{\partial \mu^D}\right)^{-1}$ is positive and have argued that the last term $\left(\tau^D\left(\frac{\partial e^{xF}}{\partial \mu^D}+\frac{\partial e^{yF}}{\partial \mu^D}\right)\right)$ is negative, and therefore state the final proposition:

Proposition 3 *Consider a region r that has an emission trading system. Then it is global welfare improving that region r imposes a CO_2 compensation on the electricity demand for the PITE producer.*

Proof. The proposition follows directly from Equation (13).

3. Numerical analysis

We supplement the theoretical model with a multi-region multi-sector numerical general equilibrium model (see e.g., Fæhn and Yonezawa, 2021). To perform a numerical simulation is useful when we want to examine the ambiguous results we derive from the theoretical analysis. Our focus is on EU and the EU ETS, where a variant of both OBA and a CO_2 compensation scheme for increased electricity prices are already in place for PITE goods. In our main analysis, we implement the CO_2 compensation as a function of electricity use as input in production (i.e., subsidy on electricity input), but also conduct sensitivity analysis with CO_2 compensation as a function of output (i.e., subsidy on output). Our main question here is to search for the optimal compensation for a given level of OBA, i.e. to study whether it is welfare-improving for the EU to introduce compensation to the PITE sectors. We will also study the consequences for the global welfare.

3.1. Data

We base our analysis on the GTAP 10 data set, which includes detailed national accounts of production and consumption (input–output tables) together with bilateral trade flows and energy-related CO_2 emissions (Aguiar et al., 2019). GTAP features 65 sectors and 141 world regions. We aggregate the data set to 10 sectors and 4 regions, reflecting our primary interest in the trade between the European Union (EU) and other major regions (see Table 1). We explicitly represent the primary and secondary energy carriers (coal, gas, crude oil, refined oil products, and electricity). This disaggregation is essential in order to distinguish energy goods by CO_2 intensity and degree of substitutability. The PITE sector is the sector in focus in our study. In addition, the aggregate data set consists of the three transport sectors (air transport, water transport, and other transport, including road and rail). All remaining sectors in the original data set are aggregated to a composite sector named “All other industries and services”.

Table 1 Model regions and sectors

Countries and regions	Sectors and commodities
European Union (EU 28)	*Energy sectors*
USA	Coal
China	Crude oil
Rest of the World	Natural gas
	Refined oil products [1]
	Electricity
	Transport sectors
	Air transport
	Water transport [1]
	Other transport [1]
	Aggregated sectors
	PITE[2]
	All other industries and services[c]

[1] OIL is part of the PITE sectors (see Appendix A).
[2] PITE—power-intensive and trade-exposed sectors: Plastics; basic metals and fabricated metal; chemicals and chemical products; other non-metallic minerals; pulp and paper, refined oil products.
[3] NETS (Non-ETS) sectors in the EU. The ETS consists of sectors that can be covered by the EU ETS. The NETS contain the remaining sectors.

3.2. Model summary

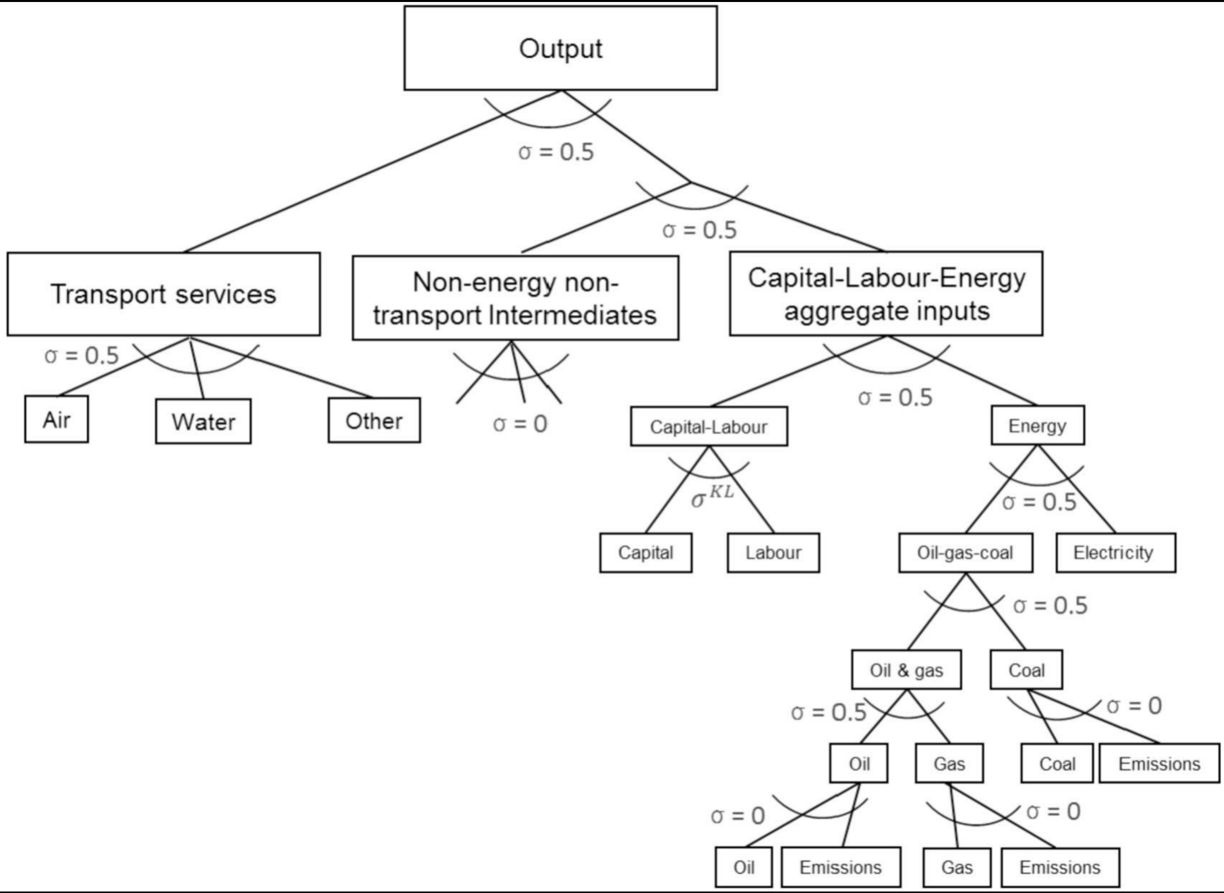
The main virtue of the detailed general equilibrium approach is its comprehensive micro-consistent representation of price-dependent market interactions. Beyond the assessment of price-induced structural change, these models allow for the quantification of efficiency and distributional implications triggered by policy measures. The production of commodities is captured by nested constant elasticity of substitution (CES) functions, describing the price-dependent use of production factors and intermediate inputs. Primary production factors included in the model are labour, capital, energy and intermediate inputs.

Capital and labour are assumed to be mobile across sectors within each region but immobile across regions. The capital is treated as a sector-specific resource in fossil fuel production. Further, factor markets are assumed to be perfectly competitive. The natural resource is only used in fossil energy production (crude oil, coal and natural gas) and is also treated as being immobile. In addition to the nesting illustrated in Figure 1, these industries have a natural resource factor added at the top of their nesting. The input factors are chosen by the producers at minimum cost subject to technological constraints.

The representative household in each region maximizes utility subject to a budget constraint. Their utilities are also modelled as CES functions. Investment and government spending are modelled as Leontief production functions, and in this static setting they are exogenous in real terms in the counterfactual simulations.

CO_2 emissions are linked in fixed proportions to the use of fossil fuels. In the different policy scenarios, emission abatement takes place by fuel switching (interfuel substitution), energy efficiency improvements (fuel/non-fuel substitution) or by reducing production and final consumption activities.

Figure 1 Nested CES structure of production technology for non-fossil fuel extraction industries



We consider the effects of assuming heterogeneous goods in the numerical simulations. That is, the bilateral trade is specified using the Armington's differentiated goods approach where domestic and foreign goods are distinguished by origin (Armington, 1969). All goods used domestically in intermediate and final household demand correspond to a CES composite that combines the domestically produced good and the good imported from other regions.

We observe and quantify the trade deficit or surplus for each region in the base-year. This balance of payment constraint is incorporated in the numerical simulation model. Public budgets, and also the composition of the budgets, are kept unchanged from the benchmark, which is ensured by lump-sum transfers.

The GTAP database provides substitution possibilities in production between primary factor inputs. The Armington elasticities are also taken from the GTAP database. For other parameters values, we either use estimates from other studies, calibrate them based on simulations of a well-established large-scale numerical simulation model or use educated guesses.

3.3. Policy scenarios

We consider the calibrated equilibrium in 2014 as a business-as-usual scenario (*BAU*). Here, all the existing taxes in the economy is removed in order to isolate the effect of the intended climate policy. Next, we implement an emission reduction target for the whole economy in the EU, distinguishing between two separated emission trading systems; EU ETS and EU non-ETS. As there is uncertainty about the future BAU path before the induced emission reduction, we simulate the policy scenarios with different economy-wide emission reduction targets. The target ranges from 20 to 30 per cent in the scenarios. In our OBA scenario (*OBA*) producers of the PITE sector receive 90 per cent of their free allowances in proportion to their output, i.e. OBA. Next, we consider the scenario where producers of the PITE good in addition receive CO_2 compensation for the costs induced by higher electricity prices due to the EU ETS (*OBA +Comp*). Whereas both OBA and CO_2 compensation are directed towards the PITE sector, other EU ETS sectors will still be competing for the available permits after the additional policy of compensation is adopted. In the *OBA + Comp* scenario we search for the compensation level that maximises welfare in EU. Neither the OBA nor the compensation will affect emissions within the EU due to the fixed emission cap, but emissions in other regions may change via changes in the leakage rate. We consider different levels of the compensation, ranging from -100 per cent to 200 per cent as a fraction of the increased electricity costs in our main scenarios. For example, 100 per cent means that the increased cost of electricity is fully compensated, while a negative value of the compensation turns it into an input tax.

3.4. Results

We investigate the effects on key indicators such as welfare, leakage rate, allowance price and production. The welfare change measure is the ratio between the scenario *OBA +Comp* and the scenario with no other anti-leakage policy than *OBA*, where regional welfare is defined as the money-metric utility of consumption. Our calculations based on EC (2020) show that the politically decided targets (as percentage changes from 2005 levels) for abating greenhouse gases is around 28 per cent in 2025 for the EU. Consider a situation with 27.5 per cent reduction for ETS and 22.5 per cent reduction for non-ETS of the benchmark EU emissions. This translates into a situation with around 25 per cent reduction of the total emissions. We consider this to be the central case in the model simulations even if this is reduction from an uncertain BAU emission level in 2025 and not the actual emission level in 2005. We also introduce scenarios in the EU with both lower and higher reduction targets than our central case. The latter is set to 20 per cent and the 30 per cent emission reduction target.

Figure 2 **EU's welfare change compared to BAU as a function of the compensation rate (relative to increased electricity costs), for 20 per cent, 25 per cent and 30 per cent emission reduction target**

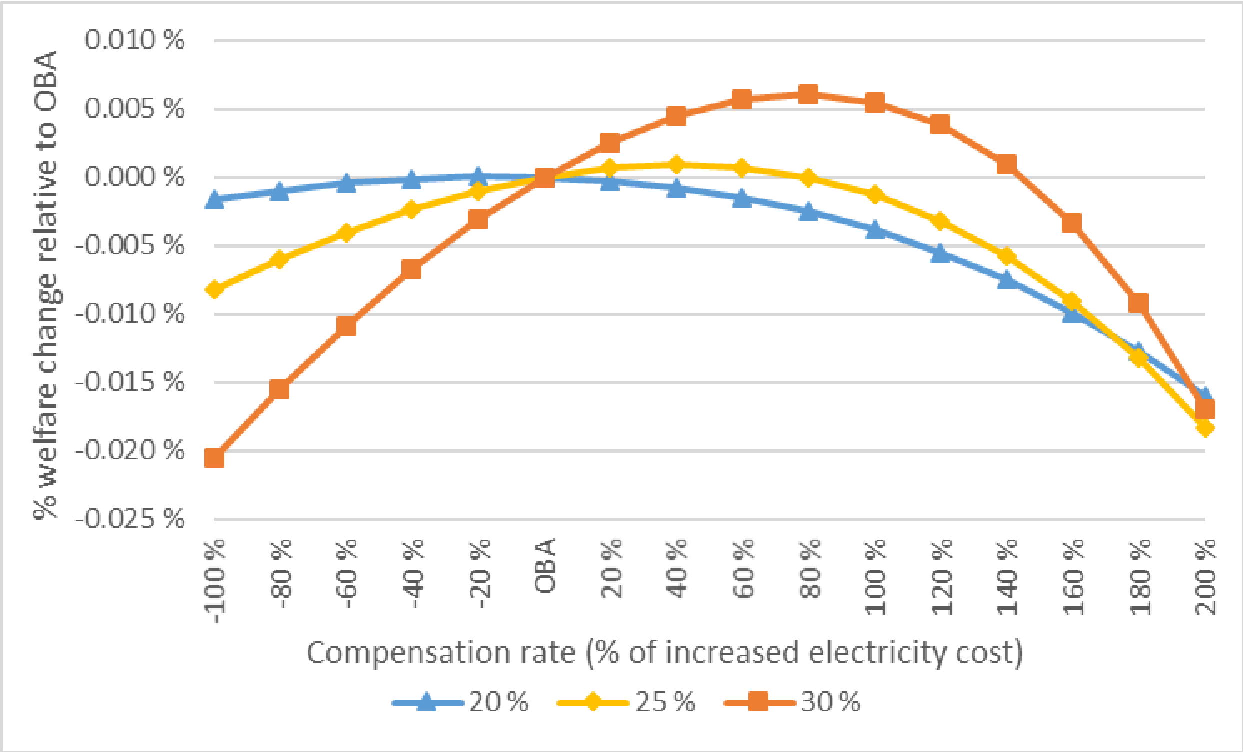
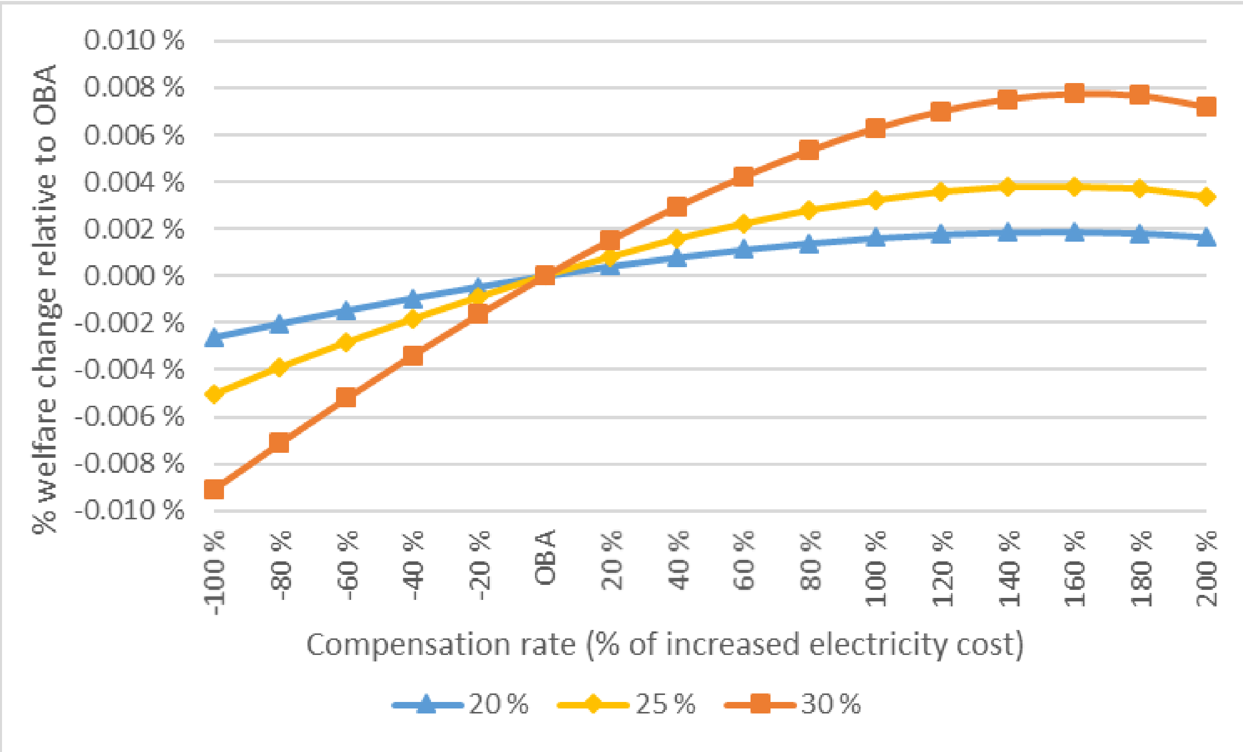


Figure 2 shows the welfare change in the EU under the different policies. With OBA displayed on the horizontal axis, the compensation rate is 0 per cent (i.e. no CO_2 compensation). The change in welfare is displayed as a percentage change compared to the only *OBA* scenario. Recall that the theoretical analysis in Section 2 suggests that the welfare effect for a region that implements a CO_2 compensation on top of the OBA depends on the terms-of-trade and reduced foreign emission. The numerical simulation suggests that a positive CO_2 compensation is welfare improving in the EU for the two most stringent emission reduction targets. Particularly, the compensation rate of increased electricity costs that maximises EU's welfare is 40 per cent with the 25 per cent emission reduction target and 80 per cent with 30 per cent emission reduction target. With an emission target of 20 per cent or lower the optimal compensation rate becomes negative. That is, the numerical simulation suggests a tax rather than a compensation for the PITE industries when the emission reduction target is lowered. Generally, the welfare impacts seem to be relatively small, as the compensation only targets the PITE sector.

The EU is a net exporter of the leakage-exposed good based on the GTAP trade data. While the EU's import of PITE goods from China is as big as the EU's export to China, the EU is a net exporter of PITE goods with other countries by big margin. For a region that implements a CO_2 compensation, the theoretical analysis in Section 2 suggested a positive effect on welfare if the sum of both the negative distortive effect of OBA[7] and the terms-of-trade effect is weaker than the positive effect of the foreign emission reduction. When we consider a situation with the emission reduction target being sufficiently strict, the optimal CO_2 compensation is positive because the benefit of reducing foreign emissions dominates the other negative effects. With increasing emission reduction target the value of reducing emission abroad increases because of a higher environmental cost of emissions. For relatively low emission reduction, however, the sum of both the negative distortive effect of the initial OBA and terms-of-trade seems to be stronger than the welfare improvement of reducing foreign emissions.

Figure 3 **Global welfare change compared to BAU as a function of the compensation rate (relative to increased electricity costs), for 20 per cent, 25 per cent and 30 per cent emission reduction target**

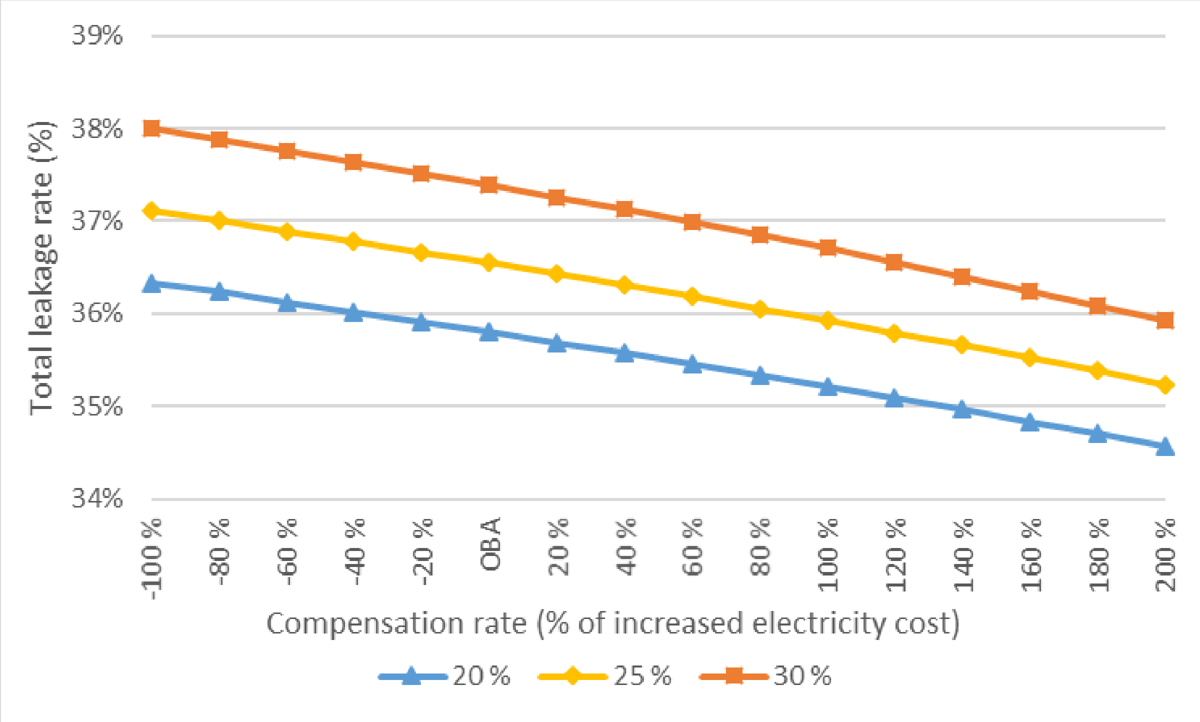


Our theoretical analysis in Section 2 suggests that the CO_2 compensation on top of the OBA in the EU has a positive effect on global welfare, if the positive effect of reduced global emission is stronger

[7] The supplementary simulations show that this effect is very small. Specifically, we simulate a scenario where we do not adjust the EU emissions reduction and include the transfer from the EU to non-EU regions in case non-EU regions are worse off, as we follow Böhringer et al. (2014). In this way, we nullify the positive effect of reducing leakage and positive terms of trade effect, and thus we can capture only the effect of strengthening the distortion of OBA.

than the negative distortive side effect of the OBA. Results illustrated in Figure 3 suggest an unambiguously positive compensation rate, for all the different stringency targets in the EU. The compensation rate of increased electricity costs that maximises global welfare is 160 per cent with all three emission reduction targets.

Figure 4 **Total leakage rate for EU as a function of the compensation rate in EUR (relative to increased electricity costs), for 20 per cent, 25 per cent and 30 per cent emission reduction target**



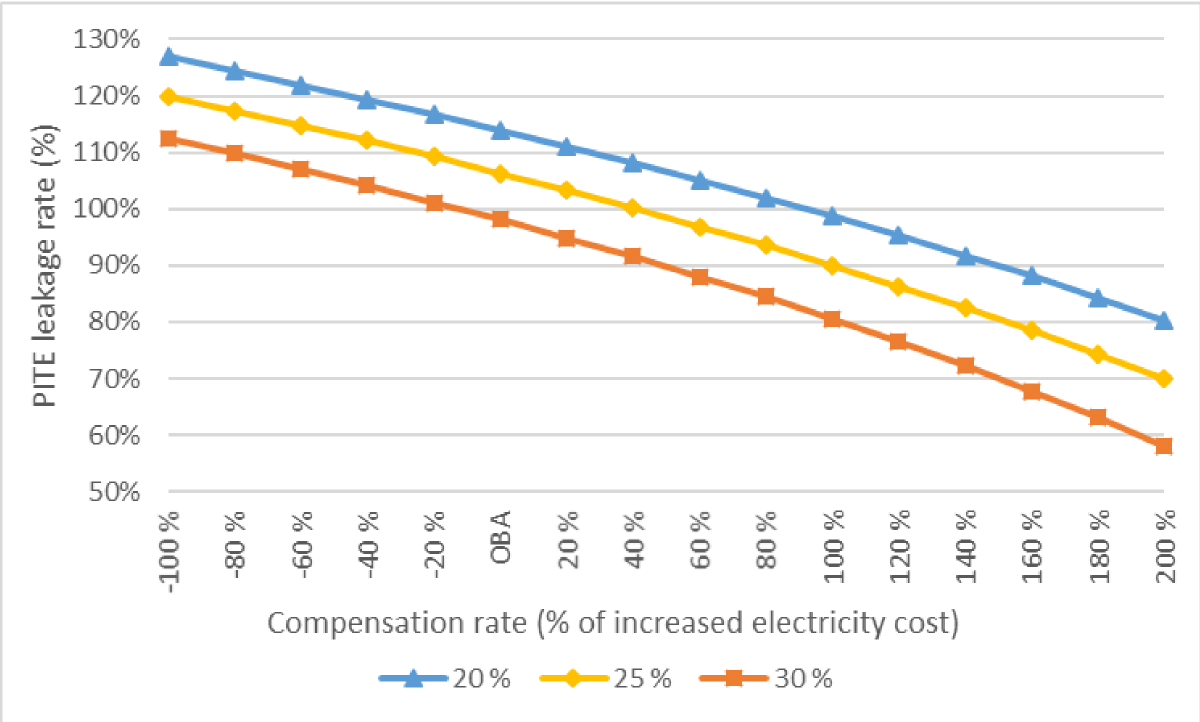
The leakage rate is defined as percentage changes in the non-abating region emissions, over emissions reduction in the abating regions (EU).[8] Figure 4 shows the economy-wide leakage rate and Figure 5 shows the leakage rate for only the PITE sectors, both for the three different emission reduction scenarios. Recall, that for a negative compensation rate, the subsidy turns in to a tax for the PITE-producers. Since this leads to a relatively higher production cost for the producers than when we only have OBA, the carbon leakage increases with increased negative compensation rate. Both Figure 4 and Figure 5 show that a positive compensation undoubtedly leads to lower carbon leakage. The leakage rate declines as increased CO_2 compensation reduces the emissions outside of the EU. Furthermore, higher emission reduction target leads to higher emission price and hence higher economy-wide carbon leakage. With an optimal compensation, in terms of EU's welfare,

[8] $Leakage\ rate\ = \frac{\Delta emissions\ from\ non-abting\ region}{\Delta emissions\ from\ abting\ region} \times 100\%.$

when the emission reduction target is 25 per cent the leakage rate in the overall economy is 36.3 per cent.

The leakage rate for the PITE industries is very sensitive to the level of compensation. This is due to the industry being vastly trade-exposed and directly affected by the compensation rate level. When the compensation rate is positive and increasing, the leakage clearly decreases compared to the case with only OBA. The optimal compensation, in terms of EU's welfare, with an emission reduction target of 25 per cent gives a leakage rate of around 100 per cent for the PITE. As expected, the leakage rate is higher for the PITE sectors as losses related to competitiveness for the sector is more pronounced. Finally, Figure 5 shows that PITE carbon leakage is in general lower with stricter emission reduction target, which might be surprising. However, the reason is that the leakage from the fossil fuel channel (i.e., lower fossil fuel price leads to the larger consumption of fuels) becomes more important in this case. For example, the leakage in electricity sector and land transport becomes more important as the emission target is increased.

Figure 5 **PITE leakage rate from EU as a function of the compensation rate in EUR (relative to increased electricity costs), for 20 per cent, 25 per cent and 30 per cent emission reduction target**

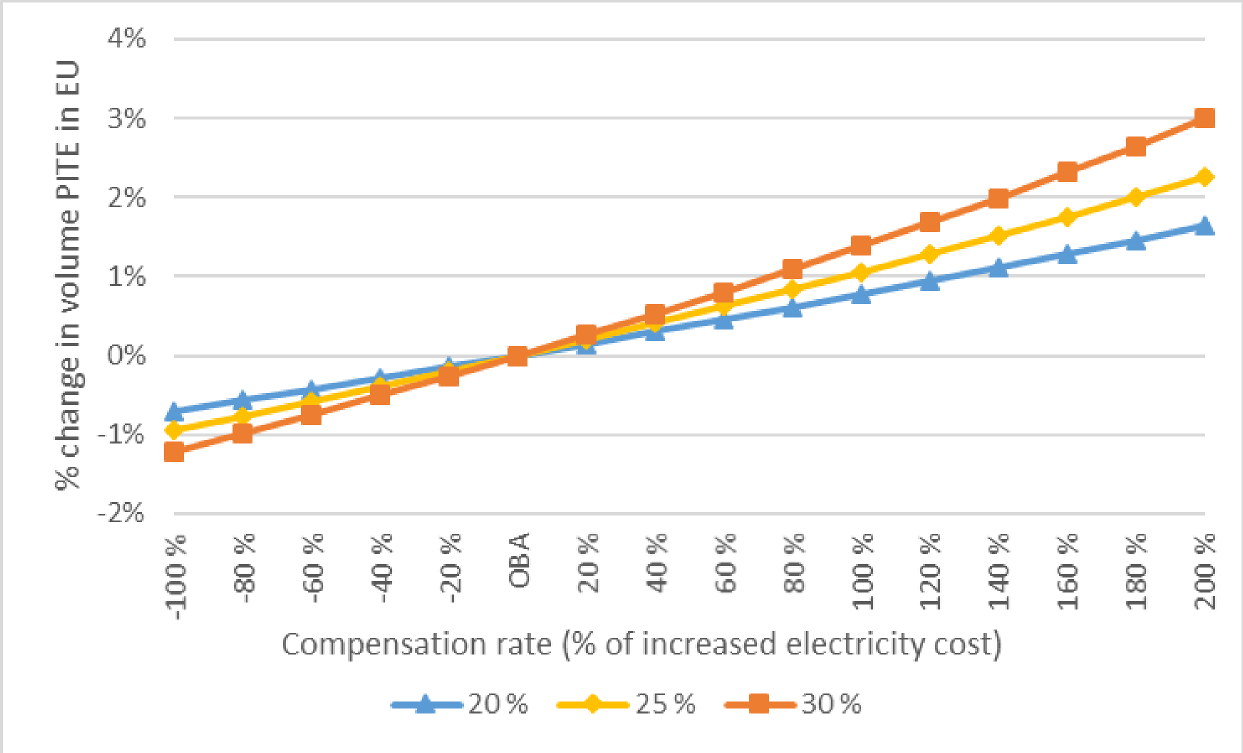


In the introduction, we describe OBA as an implicit production subsidy for the PITE industry. The CO_2 compensation, on the other hand, is an input subsidy when it is positive and a tax when it is negative. That is because it works through the electricity demand rather than towards the output as

OBA does. The effects on production of PITE in the EU is shown in Figure 6, under different compensation policies.

In our theoretical analysis in Section 2 we argue that the CO_2 compensation lowered the production cost for the PITE producer in the EU, increasing the supply on the world market and thereby lowering price of the PITE goods. Figure 6 shows that the production of PITE in the EU increases for positive values of the CO_2 compensation. As the compensation increases, the relative price of electricity in production of PITE decreases. As a result, the electricity production increases in the EU as well, though relatively less than PITE production. The optimal CO_2 compensation with 25 per cent emission reduction target, in terms of welfare change, indicates that the PITE sector increases their production volume in the EU by approximately 0.4 per cent and electricity production increases by 0.4 per cent as well. Finally, Figure 6 shows that the positive effect of the CO_2 compensation on production of PITE goods is stronger for higher emission reduction target. That is, higher emission reduction target, and thus higher emission price, in isolation reduces the competitiveness for the PITE sector as it buys 10 per cent of their allowances.[9] However, increased stringency of emission reduction leads to higher compensation and this effect weighs more and production increases.

Figure 6 **PITE output volume change in EU as a function of the compensation rate in EU (relative to increased electricity costs), for 20 per cent, 25 per cent and 30 per cent emission reduction target**



[9] Recall that the OBA rate is 90 per cent.

Positive compensation improves the competitiveness on the world market for the sectors in the EU. Table 2 summarizes the effect of the CO_2 compensation in the EU on the global PITE production. The optimal CO_2 compensation rate (relative to increased electricity costs) for the EU is shown with an underline in the table for each emission reduction target. Increased production in the EU, as a result of higher CO_2 compensation, leads to decreased production outside of the EU as the competitiveness is strengthened. Moreover, the increased production in the EU (when CO_2 compensation rates are above 100 per cent) goes along with higher global production. For the optimal CO_2 compensation with emission reduction target of 25 and 30 per cent, the global production of PITE goods increases marginally (0.02 and 0.03 per cent, respectively).

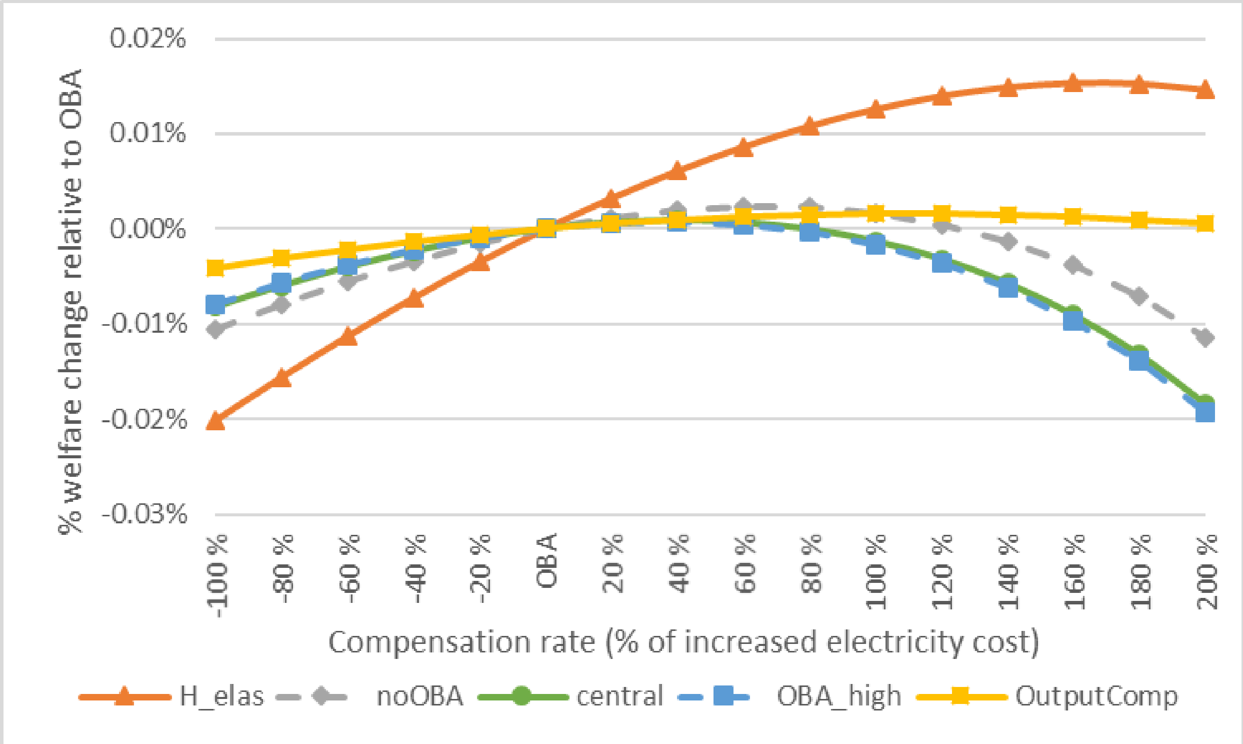
Table 2 Percentage output changes for PITE industries for different CO_2 compensations scenarios in different EU emission reduction targets where compensation rate is shown relative to increased electricity costs

Countries and regions	Emission reduction targets (20%,25%,30%)								
	20%			25%			30%		
	CO_2 compensation rate								
	-100	**<u>-20</u>**	**200**	**-100**	**<u>40</u>**	**200**	**-100**	**<u>80</u>**	**200**
EU	-0.7	-0.2	1.6	-1.0	0.4	2.3	-1.2	1.1	5.0
USA	0.1	0.0	-0.3	0.2	-0.1	-0.4	0.2	-0.2	-0.5
China	0.1	0.0	-0.2	0.1	0.0	-0.3	0.1	-0.1	-0.4
Rest of the World	0.2	0.0	-0.4	0.2	-0.1	-0.6	0.3	-0.3	-0.8
Global	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1

3.5. Sensitivity

How robust are our numerical results with respect to changes in our model assumptions? To check this, we examine the effects of changing some of our main assumptions: i) Higher (Armington) substitution elasticity, (ii) no OBA, (iii) higher OBA rate and (iv) CO_2 compensation based on output.

Figure 7 **EU's welfare change compared to BAU as a function of the compensation rate (relative to increased electricity costs), for higher Armington substitution elasticity (H_elas), no OBA (noOBA), higher OBA rate (OBA_high), CO_2 compensation based on output (OutputComp) and our central simulation from the main result (central) all with 25 per cent emission reduction target**



In our theoretical analysis, we assume homogeneous goods across regions. However, in the numerical simulations they are not homogeneous as we follow Armington formulation. With higher Armington substitution elasticities, the goods become more homogeneous. In Figure 7 we show how an alternative with a higher substitution elasticity assumption (*H_elas*) affects the optimal compensation rate in the EU. We assume an Armington substitution elasticity two times higher than the initial values in the central setting (i.e., taken from the GTAP data). From Figure 2 and Figure 7 we see that with a higher Armington substitution elasticity the welfare effects are negative with negative compensation rate (i.e., tax), but positive with positive compensation rate. Moreover, the positive welfare effect of the CO_2 compensation increases up to a level of 160 per cent compensation rate. This is mainly due to PITE goods becoming more exposed to competition with assumption of higher Armington substitution elasticity, and thus the terms-of-trade effect becoming smaller. As a result, the welfare impact is dominated by the leakage effect, and the positive effect of compensation on leakage is stronger leading to welfare improvement in the EU.

Our theoretical analysis shows that it is global welfare improving for a region to introduce the CO_2 compensation if there were no OBA, and it also implies that the regional welfare is expected to be improved as well in this case. In our central setting, we assume an OBA rate of 0.9. With both a higher OBA rate of 1 (*OBA_H*) or a no OBA (*noOBA*), the impact of welfare compared to our central assumption is not very different. However, Figure 7 shows that for negative compensation rate higher (lower) OBA rate scenario gives higher (lower) welfare effect compared to the central case. For positive compensation rate, we observe the opposite. Still, the effect compared to our central scenario is somewhat limited. For OBA rate set to 1 the optimal compensation rate is still 40 per cent. With no OBA, the optimal compensation is 60 per cent, and the welfare impact is improved as the theoretical analysis implies. As for global welfare, we find the optimal compensation to be at least 200 per cent, compared to 160 per cent our in central assumption.

In our main analysis, we present the CO_2 compensation as a function of the increase in electricity price and electricity use as input in production. Note that in reality electricity price change is affected by many things as well as allowance price, but in the model, we can directly observe the electricity price change in the scenario of the increased allowance price. However, for some sectors in the EU this compensation is a function of increase in output. This setting is similar to the OBA, as the compensation is now based on the output (and not electricity input). In Figure 7 we show how this setting would affect the result (*OutputComp*). The effect on EU's welfare is limited compared to our central scenario. For both negative and positive compensation, the welfare effect is above the central simulation, and the result suggests an optimal compensation rate of 120 per cent. This is likely due to the distortion between electricity input and other inputs not occurring anymore, and thus the larger subsidy is justified as it reduces leakage without incurring extra distortion.

4. Concluding remarks

Unilateral CO_2 emission reduction can lead to carbon leakage, such as relocation of power-intensive and trade-exposed industries. As a result, these industries in the EU receive a large number of free allowances to mitigate the leakage. This is a free allowance allocation system conditional on output and is often referred to as output-based allocation. In the EU emission trading system these industries are also subjected to higher cost of electricity due to emission pricing in this sector. For that reason, these industries also receive CO_2 compensation due to higher indirect cost, also to mitigate leakage.

This paper examines the welfare effects of supplementing free allowances with CO_2 compensation to the power-intensive and trade-exposed industries. The European Commission has suggested to start introducing a carbon border adjustment mechanism scheme gradually as from 2026 at the earliest. However, there is still great uncertainty about how the system of CBAM finally will be designed. Nevertheless, existing instruments of free allowances and the indirect compensation for increased costs due to higher electricity prices that are designed to dampen carbon leakage are intended to be prolonged at least to 2026 and may co-exist with a carbon border adjustment mechanism in one form or the other until 2035.

We derive a theoretical model and the main analytical results suggest that introducing CO_2 compensation would have a regional and global welfare improving effect under certain plausible conditions. We supplement the theoretical model with simulations of a multi-region multi-sector numerical simulation model. The main question here is to search for the optimal compensation for a given level of output-based allocation, i.e. to study whether it is welfare-improving for the EU to introduce compensation to the power-intensive sectors. While both OBA and CO_2 compensation are associated with the allowance price, the compensation is connected to electricity input in production and OBA to the production itself and, thus, the effects of the two instruments will most likely be different. We also study the consequences for the global welfare. In addition, we examine the effects on carbon leakage rate, emissions and production of the power-intensive goods.

Numerical simulations in the context of the EU ETS support the analytical findings of increased regional welfare of introducing compensation if the emission reduction target is stringent enough, which is the case regarding the climate policy in the EU. The optimal CO_2 compensation is positive because the benefit of reducing foreign emissions dominates the sum of both the negative distortive effect of free allowance allocation and the terms-of-trade effect.

We also show that the optimal compensation rate is unambiguously positive for global welfare for all the different stringency targets in the EU. Further, we show that increased optimal compensation leads to reduced leakage and increased production of the power-intensive and trade-exposed goods. We perform a set of sensitivity analysis that confirms our results.

Supplemental polices, such as output-based allocation and the indirect CO_2 compensation for increased costs due to higher electricity prices, have been heavily argued for by the domestic power-intensive and trade-exposed industry as necessary support in order to mitigate carbon leakage and ensure competitiveness for the domestic producers within EU on the world market. With great uncertainty about the final design of Carbon Border Adjustment Measure, particularly towards the scope of the emissions, the industry seems to argue that the existing instruments must co-exist with the planned Carbon Border Adjustment Measure. Our analysis has focused on solely the existing instruments in order to clarify the fundamental economic effects. Further, if the Carbon Border Adjustment Measure only will cover direct emissions, our analysis of the CO_2 compensation would be highly relevant as compensation is for the indirect emissions of electricity input. Further research will be necessary to study the effects of combining the existing instruments with CBAM. As for now, the analysis suggests that a CO_2 compensation is an effective policy strategy to mitigate carbon leakage in EU.

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Appendix A. List of power intensive and trade exposed industries that receive compensation

EU carbon leakage list with compensation before or after 2020. NACE code and sector-	**Compensation list until 2020**	**Compensation new list 2021**
07.10 Mining of iron ores	Quarrying of iron ore	
14.11 Manufacture of leather clothes		Manufacture of leather clothes
17.11 Manufacture of pulp	Production of mechanical pulp	Manufacture of pulp
17.12 Manufacture of paper and paperboard	Production of cardboard and paper	Manufacture of paper and paperboard
19.20 Manufacture of refined petroleum products		Manufacture of refined petroleum products
20.11 Manufacture of industrial gases		Industrial gases: Hydrogen (20.11.11.50); Inorganic oxygen compounds of non-metal (20.11.12.90)
20.13 Manufacture of other inorganic basic chemicals	Production of other inorganic chemical	Manufacture of other inorganic basic chemicals
20.14 Manufacture of other organic basic chemicals	Production of other organic chemical raw materials	
20.15 Manufacture of fertilisers and nitrogen compounds	Production of fertilizers and nitrogen products	
20.16 Manufacture of plastics in primary forms	Production of base plastic	Plastics sector: Polyethylene in primary forms (20.16.40.15)
23.14 Manufacture of glass fibres		Glass fibre sector: Glass fibre mats (23.14.12.10); Glass fibre voiles (23.14.12.30)

24.10 Manufacture of basic iron and steel and of ferro-alloys	Production of iron, steel and ferro-alloys	Manufacture of basic iron and steel and ferro-alloys
24.42 Aluminium production	Production of aluminium	Production of aluminium
24.43 Lead, zinc and tin production	Production of lead, zinc and tin	Lead, zinc and tin production
24.44 Copper production	Copper production	Copper production
24.45 Other non-ferrous metal production		Other non-ferrous metal production
24.51 Casting of iron		Casting of iron sector

Source: EC- European Commission (2021b)

Appendix B. Derivation of regional welfare function

We differentiate the regional welfare function w.r.t. the CO_2 compensation μ^D:

$$\frac{\partial W^D}{\partial \mu^D} = u_{\bar{x}}^D \frac{\partial \bar{x}^D}{\partial \mu^D} + u_{\bar{y}}^D \frac{\partial \bar{y}^D}{\partial \mu^D} + u_{\bar{z}}^D \frac{\partial \bar{z}^D}{\partial \mu^D} - c_x^{xD} \frac{\partial x^D}{\partial \mu^D} - c_e^{xD} \frac{\partial e^{xD}}{\partial \mu^D} - c_y^{yD} \frac{\partial y^D}{\partial \mu^D} - c_e^{yD} \frac{\partial e^{yD}}{\partial \mu^D} - c_{\tilde{x}}^{yD} \frac{\partial \tilde{x}^D}{\partial \mu^D} - c_z^{zD} \frac{\partial z^D}{\partial \mu^D}$$
$$- \tau^D \left[\frac{\partial e^{xD}}{\partial \mu^D} + \frac{\partial e^{yD}}{\partial \mu^D} + \frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right]$$

With the conditions and assumptions from Eqs. (4), (5) and (7) we get:

$$= p^{xD} \frac{\partial \bar{x}^D}{\partial \mu^D} + p^y \frac{\partial \bar{y}^D}{\partial \mu^D} + p^z \frac{\partial \bar{z}^D}{\partial \mu^D} - p^{xD} \frac{\partial x^D}{\partial \mu^D} + t^D \frac{\partial e^{xD}}{\partial \mu^D} - (p^y + o^D) \frac{\partial y^D}{\partial \mu^D} + t^D \frac{\partial e^{yD}}{\partial \mu^D} + (p^{xD} - \mu^D) \frac{\partial \tilde{x}^D}{\partial \mu^D} - p^z \frac{\partial z^D}{\partial \mu^D}$$
$$- \tau^D \left[\frac{\partial e^{xD}}{\partial \mu^D} + \frac{\partial e^{yD}}{\partial \mu^D} + \frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right]$$

$$= p^{xD} \left(\frac{\partial \bar{x}^D}{\partial \mu^D} + \frac{\partial \tilde{x}^D}{\partial \mu^D} - \frac{\partial x^D}{\partial \mu^D}\right) + p^y \left(\frac{\partial \bar{y}^D}{\partial \mu^D} - \frac{\partial y^D}{\partial \mu^D}\right) + p^z \left(\frac{\partial \bar{z}^D}{\partial \mu^D} - \frac{\partial z^D}{\partial \mu^D}\right) + t^D \left(\frac{\partial e^{xD}}{\partial \mu^D} + \frac{\partial e^{yD}}{\partial \mu^D}\right) - o^D \frac{\partial y^D}{\partial \mu^D} - \mu^D \frac{\partial \tilde{x}^D}{\partial \mu^D}$$
$$- \tau^D \left[\frac{\partial e^{xD}}{\partial \mu^D} + \frac{\partial e^{yD}}{\partial \mu^D} + \frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right]$$

From Eq. (2) we have that there is no trade between the two regions of good x. By differentiating the trade assumption w.r.t. μ^D we have that, $\frac{\partial x^D}{\partial \mu^D} = \frac{\partial \bar{x}^D}{\partial \mu^D} + \frac{\partial \tilde{x}^D}{\partial \mu^D}$. We can further simplify:

$$= p^y \left(\frac{\partial \bar{y}^D}{\partial \mu^D} - \frac{\partial y^D}{\partial \mu^D}\right) + p^z \left(\frac{\partial \bar{z}^D}{\partial \mu^D} - \frac{\partial z^D}{\partial \mu^D}\right) + t^D \left(\frac{\partial e^{xD}}{\partial \mu^D} + \frac{\partial e^{yD}}{\partial \mu^D}\right) - o^D \frac{\partial y^D}{\partial \mu^D} - \mu^D \frac{\partial \tilde{x}^D}{\partial \mu^D}$$
$$- \tau^D \left[\frac{\partial e^{xD}}{\partial \mu^D} + \frac{\partial e^{yD}}{\partial \mu^D} + \frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right]$$

By differentiating the emission constraint from Eq. (1) w.r.t. to the CO_2 compensation μ^D, we have that: $\frac{\partial \bar{\bar{E}}^D}{\partial \mu^D} = \frac{\partial e^{xD}}{\partial \mu^D} + \frac{\partial e^{yD}}{\partial \mu^D} = 0$. Hence, we can simplify further:

$$= p^y \left(\frac{\partial \bar{y}^D}{\partial \mu^D} - \frac{\partial y^D}{\partial \mu^D}\right) + p^z \left(\frac{\partial \bar{z}^D}{\partial \mu^D} - \frac{\partial z^D}{\partial \mu^D}\right) - o^D \frac{\partial y^D}{\partial \mu^D} - \mu^D \frac{\partial \tilde{x}^D}{\partial \mu^D} - \tau^D \left[\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right]$$

Further, we differentiate the balance-of-payment constraint in Eq. (8) w.r.t the CO_2 compensation μ^D:

$$\frac{\partial p^y}{\partial \mu^D}(y^D - \bar{y}^D) + p^y \left(\frac{\partial y^D}{\partial \mu^D} - \frac{\partial \bar{y}^D}{\partial \mu^D}\right) + \frac{\partial p^z}{\partial \mu^D}(z^D - \bar{z}^D) + p^z \left(\frac{\partial z^D}{\partial \mu^D} - \frac{\partial \bar{z}^D}{\partial \mu^D}\right) = 0$$

Solving for p^z and inserting the result into the equation gives us:

$$= p^y\left(\frac{\partial \bar{y}^D}{\partial \mu^D} - \frac{\partial y^D}{\partial \mu^D}\right) + \left[\frac{\frac{\partial p^y}{\partial \mu^D}(y^D - \bar{y}^D) + p^y\left(\frac{\partial y^D}{\partial \mu^D} - \frac{\partial \bar{y}^D}{\partial \mu^D}\right) + \frac{\partial p^z}{\partial \mu^D}(z^D - \bar{z}^D)}{-\left(\frac{\partial z^D}{\partial \mu^D} - \frac{\partial \bar{z}^D}{\partial \mu^D}\right)}\right]\left(\frac{\partial \bar{z}^D}{\partial \mu^D} - \frac{\partial z^D}{\partial \mu^D}\right) - o^D\frac{\partial y^D}{\partial \mu^D} - \mu^D\frac{\partial \tilde{x}^D}{\partial \mu^D} - \tau^D\left[\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right]$$

$$= -o^D\frac{\partial y^D}{\partial \mu^D} - \mu^D\frac{\partial \tilde{x}^D}{\partial \mu^D} + \frac{\partial p^y}{\partial \mu^D}(y^D - \bar{y}^D) + \frac{\partial p^z}{\partial \mu^D}(z^D - \bar{z}^D) - \tau^D\left[\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right]$$

and we finally arrive at :

$$\mu^{D^*} = \frac{\left[-o^D\frac{\partial y^D}{\partial \mu^D} + \frac{\partial p^y}{\partial \mu^D}(y^D - \bar{y}^D) + \frac{\partial p^z}{\partial \mu^D}(z^D - \bar{z}^D) - \tau^D\left(\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D}\right)\right]}{\frac{\partial \tilde{x}^D}{\partial \mu^D}} \tag{10}$$

Appendix C. Derivation of global welfare function

We differentiate the global welfare w.r.t. the CO_2 compensation μ^D in region *D*:

$$\frac{\partial W^G}{\partial \mu^D} = \sum\nolimits_{r=D,F} \left[u_{\bar{x}}^r \frac{\partial \bar{x}^r}{\partial \mu^D} + u_{\bar{y}}^r \frac{\partial \bar{y}^r}{\partial \mu^D} + u_{\bar{z}}^r \frac{\partial \bar{z}^r}{\partial \mu^D} - c_x^{xr} \frac{\partial x^r}{\partial \mu^D} - c_e^{xr} \frac{\partial e^{xr}}{\partial \mu^D} - c_y^{yr} \frac{\partial y^r}{\partial \mu^D} - c_e^{yr} \frac{\partial e^{yr}}{\partial \mu^D} - c_{\tilde{x}}^{yr} \frac{\partial \tilde{x}^r}{\partial \mu^D} - c_z^{zr} \frac{\partial z^r}{\partial \mu^D} - \tau^D \left(\frac{\partial e^{xr}}{\partial \mu^D} + \frac{\partial e^{yr}}{\partial \mu^D} \right) \right]$$

With the conditions and assumptions from Eqs. (2), (4), (5) and (7) we get:

$$= \sum\nolimits_{r=D,F} \left[p^{xr} \left(\frac{\partial \bar{x}^r}{\partial \mu^D} + \frac{\partial \tilde{x}^r}{\partial \mu^D} - \frac{\partial x^r}{\partial \mu^D} \right) + p^y \left(\frac{\partial \bar{y}^r}{\partial \mu^D} - \frac{\partial y^r}{\partial \mu^D} \right) + p^z \left(\frac{\partial \bar{z}^r}{\partial \mu^D} - \frac{\partial z^r}{\partial \mu^D} \right) \right] + t^D \left(\frac{\partial e^{xD}}{\partial \mu^D} + \frac{\partial e^{yD}}{\partial \mu^D} \right) - o^D \frac{\partial y^D}{\partial \mu^D} - \mu^D \frac{\partial \tilde{x}^D}{\partial \mu^D} - \tau^D \left(\frac{\partial e^{xD}}{\partial \mu^D} + \frac{\partial e^{yD}}{\partial \mu^D} + \frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D} \right)$$

By differentiating Eq. (1) w.r.t. μ^D and assuming no trade across regions of good x we have:

$$= \sum\nolimits_{r=D,F} \left[p^y \left(\frac{\partial \bar{y}^r}{\partial \mu^D} - \frac{\partial y^r}{\partial \mu^D} \right) + p^z \left(\frac{\partial \bar{z}^r}{\partial \mu^D} - \frac{\partial z^r}{\partial \mu^D} \right) \right] - o^D \frac{\partial y^D}{\partial \mu^D} - \mu^D \frac{\partial \tilde{x}^D}{\partial \mu^D} - \tau^D \left(\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D} \right)$$

Differentiating the balance-of-payment constraint Eq. (8) w.r.t. CO_2 compensation μ^D gives us:

$$\frac{\partial p^y}{\partial \mu^D} (y^r - \bar{y}^r) + p^y \left(\frac{\partial y^r}{\partial \mu^D} - \frac{\partial \bar{y}^r}{\partial \mu^D} \right) + \frac{\partial p^z}{\partial \mu^D} (z^r - \bar{z}^r) + p^z \left(\frac{\partial z^r}{\partial \mu^D} - \frac{\partial \bar{z}^r}{\partial \mu^D} \right) = 0$$

Solving for p^z and inserting into the equation gives us:

$$= \sum\nolimits_{r=D,F} \left[p^y \left(\frac{\partial \bar{y}^r}{\partial \mu^D} - \frac{\partial y^r}{\partial \mu^D} \right) + \left(\frac{\frac{\partial p^y}{\partial \mu^D} (y^r - \bar{y}^r) + p^y \left(\frac{\partial y^r}{\partial \mu^D} - \frac{\partial \bar{y}^r}{\partial \mu^D} \right) + \frac{\partial p^z}{\partial \mu^D} (z^r - \bar{z}^r)}{-\left(\frac{\partial z^r}{\partial \mu^D} - \frac{\partial \bar{z}^r}{\partial \mu^D} \right)} \right) \left(\frac{\partial \bar{z}^r}{\partial \mu^D} - \frac{\partial z^r}{\partial \mu^D} \right) \right] - o^D \frac{\partial y^D}{\partial \mu^D} - \mu^D \frac{\partial \tilde{x}^D}{\partial \mu^D} - \tau^D \left(\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D} \right)$$

and this equation can further be simplified to:

$$= \sum\nolimits_{r=D,F} \left[\frac{\partial p^y}{\partial \mu^D} (y^r - \bar{y}^r) + \frac{\partial p^z}{\partial \mu^D} (z^r - \bar{z}^r) \right] - o^D \frac{\partial y^D}{\partial \mu^D} - \mu^D \frac{\partial \tilde{x}^D}{\partial \mu^D} - \tau^D \left(\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D} \right)$$

With our assumption from Eq. (2):

$$y^D + y^F = \bar{y}^D + \bar{y}^F$$

$$z^D + z^F = \bar{z}^D + \bar{z}^F$$

we can rewrite the equation as:

$$= -o^D \frac{\partial y^D}{\partial \mu^D} - \mu^D \frac{\partial \tilde{x}^D}{\partial \mu^D} - \tau^D \left(\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D} \right)$$

Solving for the optimal CO_2 compensation we finally arrive at :

$$\mu^{D^{G*}} = \frac{\left[-o^D \frac{\partial y^D}{\partial \mu^D} - \tau^D \left(\frac{\partial e^{xF}}{\partial \mu^D} + \frac{\partial e^{yF}}{\partial \mu^D} \right) \right]}{\frac{\partial \tilde{x}^D}{\partial \mu^D}} \tag{12}$$