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Compensation for Indirect Carbon Costs – Impacts on Electricity Efficiency, Production, and Emissions*

by

Cathrine Hagem[1,ξ], Snorre Kverndokk[2] and
Knut Einar Rosendahl [1,3]

[1]Statistics Norway, Research Department
[2]Ragnar Frisch Centre for Economic Research
[3]Norwegian University of Life Sciences

Abstract

The EU Emissions Trading System (EU ETS) leads to higher electricity prices and thus higher costs for electricity-intensive industries in the EU, reducing their competitiveness compared to those in non-EU countries. This disparity may result in carbon leakage, where production shifts abroad, potentially increasing global emissions. To mitigate this, the EU introduced a compensation scheme in 2012, allowing member states to compensate affected industries for the higher electricity prices. This paper explores analytically and numerically the effects of this compensation scheme on production, electricity efficiency, and emissions. We find that while the EU ETS price signal reduces production and increases electricity efficiency, the compensation scheme can counteract these effects by boosting production and potentially reducing electricity efficiency. Additionally, conditional decarbonization or energy efficiency efforts may lead to socially inefficient investments and could have undesired impacts on electricity efficiency. These findings highlight the complex trade-offs in designing effective climate policies that balance environmental goals with industrial competitiveness.

Keywords: Climate policy, EU-ETS, CO_2 compensation, electricity efficiency

JEL classification: D21, H23, Q52

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ξ Corresponding author: Cathrine Hagem.E-mail: cah@ssb.no

1. Introduction

The EU Emissions Trading System (EU ETS) affects the price of electricity consumption since fossil-based electricity generators that constitute a substantial share of EU generation, have to pay a significant price for their emissions. A large part of this additional cost is passed on to consumers through higher electricity prices. Many manufacturing industries have both high emissions and a large use of electricity, and are therefore hit by the ETS both directly via the carbon price and indirectly via higher electricity prices. Carbon pricing can therefore lead to reduced competitiveness for these industries, compared to producers in other countries who typically do not have equivalent carbon prices. This can increase production and thus emissions in the latter group at the expense of production in the EU, implying so-called carbon leakage.

To limit this effect, the EU has on the one hand allocated large amounts of free allowances to deal with the direct cost effect mentioned above. In addition, the EU allows countries to compensate power intensive and trade-exposed (PITE) industries for the indirect cost effects due to increased electricity prices (EU, 2012), henceforth referred to as the compensation scheme. It is up to each country to decide whether they want to use this compensation opportunity. But if they do, they must follow state-aid policy and the EU guidelines.[1] The compensation is allocated to eligible trade-exposed firms based on either their production of goods or their use of electricity. Countries must finance this scheme themselves. Almost half of the countries in the European Economic Area (EEA) – including countries with major electricity-intensive industries such as Germany, France, Finland and Norway – have established compensation schemes; most of them pay the maximum allowable amount to the eligible sectors (Næss-Schmidt et al., 2019; ERST et al., 2020; EU, 2020).

In 2020, the Commission adopted revised guidelines for the compensation scheme (EU, 2020). One of the main revisions was that compensation was related to ongoing production/electricity use and not based on historical numbers (grandfathering). Another main revision was that compensation was made conditional upon additional decarbonization or energy efficiency efforts by the firms concerned.

For instance, to qualify for compensation in the German scheme, the beneficiaries must inter alia invest at least 50 percent of the aid amount to improve energy management systems or

[1] EU (2012) states which kind of economic activities (specified by NACE-codes) may be eligible for compensation. No other sectors and subsectors will be considered eligible for such aid.

decarbonize the production process.[2] The Norwegian government has recently introduced changes to the compensation scheme.[3] One significant change is a requirement that 40% of the compensation amount must be used for measures that contribute to emission reductions or energy efficiency at facilities.

In this article, we discuss how the design of the mechanism may affect production (and thereby carbon leakage and employment), energy efficiency, and emission. We explore analytically the potential impact of making the compensation conditional on decarbonization or energy efficiency efforts, distinguishing between emissions requirement and electricity efficiency requirement.

As mentioned above, the compensation scheme comes in addition to the large amount of free emission allowances to sectors regulated by EU ETS which are "exposed to significant risk of carbon leakage".[4] Electricity- and emissions intensive, trade-exposed producers will benefit from both policy measures aimed at reducing carbon leakage. The impacts of free emission allowances have been extensively analyzed in the literature (see inter alia Felder and Rutherford, 1993; Jensen and Rasmussen, 2000; Böhringer and Lange, 2005; Fischer and Fox, 2010; Böhringer et al., 2017, 2025; Kaushal and Rosendahl, 2020). Most of the focus has been on output-based allocation, where allocation to a firm is proportional to its production (i.e., similar to the compensation scheme, and also quite similar to the allocation rules in the EU ETS). A main finding from this literature is that whereas output-based allocation improves competitiveness and may be welfare-improving compared to carbon pricing alone, there exist better measures (e.g., carbon border adjustments or combining free allocation with a consumption tax).

Although substantial funds have already been disbursed under the compensation scheme, there has been surprisingly little research on this mechanism and its effects. In 2023, 15 Member States paid indirect costs caused by the EU ETS incurred in 2022. Their total payments were equivalent to 16% of their 2022 auction revenue (EU, 2023).[5]

We are aware of three ex-post empirical analyses that study effects of the compensation scheme at the firm level. Ferrara and Giua (2022) studies the impact on the performance of aided firms in

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[2] https://ec.europa.eu/commission/presscorner/detail/es/ip_22_4925
[3] Norway is not a member of the EU, but participates in EU ETS as a member of the EEA.
[4] EU (2019) provides a list of sectors and subsectors deemed at risk of carbon leakage for the years 2021–2030 (specified by NACE-codes) and thereby entitled to free allowances.
[5] This share was substantially larger for Norway, see, e.g., Wettestad and Hagem (2024).

EU in 2009–2017, whereas Wang (2024) investigates the impact of the compensation subsidy on firm performance in Finland in the period 2016– 2020. Neither of the studies find any significant effect on firms' competitiveness. As compensation for the period 2012-2020 was based on historical and not ongoing activity levels, the impact on competitiveness can be expected to be larger under the revised regulations for the post 2020 period. Basaglia et al. (2025) study empirically the effects of the compensation scheme on UK manufacturing firms. They start with a simple theoretical model that predicts lower reductions in production and electricity use with the compensation scheme than without, and that compensated and uncompensated firms have the same incentives to invest in electricity-saving technology. This means that energy efficiency is unaffected by the compensation scheme. The empirical results confirm the predictions. Compensating for indirect carbon costs increases output, electricity consumption and emissions. They did not find any significant effects on energy efficiency.

Kaushal et al. (2023) examine the regional and global welfare effects of supplementing free allowances with compensation to the PITE industries. Their numerical CGE-model results suggest that the present design of compensation scheme has regional and global welfare improving effects under certain plausible conditions as it reduces carbon leakages. However, the analysis does not incorporate the demand for additional decarbonization efforts included in the revised regulation of the compensation (EU, 2020).

The purpose of this paper is to shed some light on potential impacts of the revised regulation of compensation. Our analytical model is different than the simple model in Basaglia et al. (2025) in many ways. We specify a production function which makes us able to study in more detail effects on electricity efficiency. Second, we also model different ways the emissions occur in the production process, which has an implication on the results. Finally, we compare results before and after the revised regulation of compensation, to see the effects of the regulation.

More specifically, we explore the following research question: *What are the expected impacts of the compensation scheme on production, electricity consumption, emissions and electricity efficiency?*

We find the following conclusions:

The indirect emission costs following from the EU ETS lead to lower production, and hence potential for carbon leakages, but they also reduce emissions and increase the electricity efficiency of the sector, which is in line with the goals of the green transition.

The compensation for the indirect emission costs following from the EU ETS leads to higher production, and hence potential for reduced carbon leakages, compared to the case with no compensation, but it reduces the electricity efficiency of the sector and increases emissions, which goes against the goals of the green transition.

The guidelines for the compensation scheme are designed to avoid overcompensation compared to a situation before the EU ETS, for all sectors. However, we cannot rule out that the scheme compensates more than the actual indirect cost increase due to higher electricity prices. Furthermore, new production technologies may imply that the compensation scheme reduces electricity efficiency compared to a situation without the EU ETS price signals.

When compensation is made conditional upon additional decarbonization efforts by the firms concerned, socially inefficient decarbonization efforts may be implemented. Furthermore, these investments may also decrease electricity efficiency. We also find that compensation with energy efficiency requirements will incentivize investments which leads to lower electricity productivity, compared to compensation without such requirements.

In the next section we present the analytical model, which is the starting point of our analysis. In section 3, we apply the model to the EU ETS and the compensation scheme and introduce the four scenarios which help us to analyze the impacts of the scheme. Sections 4-6 present and compare the outcome of the scenarios, while concluding remarks are given in section 7.

2. Model.

We consider a firm in the PITE (power intensive and trade-exposed) industry with a Cobb-Douglas production (Q) function of electricity (E) and other input factors such as capital (K), where α and β are output elasticities:[6]

$$(1)\, Q = f(E,K) = AE^{\alpha}K^{\beta}, \quad \alpha > 0,\ \beta > 0, \qquad \alpha + \beta < 1$$

Although K may comprise various input factors, we will henceforth refer to K as capital. We assume that labor is not included in K, but is proportional with output.[7] Furthermore, we assume that the production sector under consideration is a price taker in all markets. Let p denote the effective price received per unit of Q, net of the cost of labor per unit production, and e and k denote the effective price paid per unit of E and K, respectively. We use the term *effective price* as we later incorporate emission cost and subsidies in the prices.

The producer's profit maximization problem is

$$(2)\, \text{Max } \Pi = pQ - eE - kK,$$

with respect to E and K, given equation (1) .

By deriving the 1. order conditions and rearranging, we get:

$$(3)\, \frac{E}{K} = \frac{\alpha}{\beta}\frac{k}{e}, \quad \frac{E}{Q} = \frac{p\alpha}{e}, \quad \frac{K}{Q} = \frac{p\beta}{k},$$

Furthermore, we find (see Appendix A):[8]

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[6] As is common in these types of models, we assume decreasing returns to scale in E and K. This can be justified by fixed factors such as technology, or limited access to some crucial input factors implicitly captured by A (e.g. skilled labor or natural resources).

[7] A justification for this assumption is that labor accounts for a small share of inputs in most PITE sectors, and that there is generally low substitutability between labor and capital/electricity in these industries. We seek to keep the model as simple as possible, and capital and electricity are more relevant input factors with respect to the compensation scheme.

[8] We use differentials to explore how small changes in exogenous variables affect the outcome of E, K and Q in the firm's profit maximizing optimum. For large changes in the variable, the results should be interpreted with more caution and numerical calculations will be applied to confirm the results.

$$\frac{dE}{de}=\frac{1}{N}\frac{\beta(\beta-1)Q}{K^2}<0,\quad \frac{dE}{dk}=-\frac{1}{N}\frac{\alpha\beta Q}{EK}<0,\quad \frac{dE}{dp}=\frac{1}{N}\frac{\alpha\beta Q^2}{EK^2}>0$$

$$(4)\ \frac{dK}{de}=-\frac{1}{N}\frac{\alpha\beta Q}{EK}<0,\quad \frac{dK}{dk}=\frac{1}{N}\frac{\alpha(\alpha-1)Q}{E^2}<0,\quad \frac{dK}{dp}=\frac{1}{N}\frac{\alpha\beta Q^2}{E^2K}>0$$

$$\frac{dQ}{de}=-\frac{1}{N}\frac{Q^2\alpha\beta}{EK^2}<0,\quad \frac{dQ}{dk}=-\frac{1}{N}\frac{Q^2\alpha\beta}{E^2K}<0,\quad \frac{dQ}{dp}=\frac{1}{N}\frac{\alpha\beta Q^3}{E^2K^2}(\alpha+\beta)>0$$

where $N=p\left[f''_{EE}\cdot f''_{KK}-(f''_{EK})^2\right]>0$, and the term in the bracket is the second order condition for profit maximization.

Both electricity, capital and total production are decreasing in *e* and increasing in *p*. These are all well-known properties of a Cobb Douglas production function defined by (1) due to the implicit complementarity of the input factors. This follows from the positive cross derivatives ($f''_{EK}=\frac{\alpha\beta Q}{EK}>0$). Thus, both input factors are decreasing in the price of the other.

Moreover, using (3), we get

$$(5)\ d\frac{E}{Q}=\frac{\alpha}{e}dp-\frac{\alpha p}{e^2}de=\frac{\alpha}{e}\left[dp-\frac{p}{e}de\right],$$

such that

$$(6)\ d\frac{E}{Q}>0\quad for=\frac{dp}{p}>\frac{de}{e}$$

Thus, electricity efficiency is decreasing (*E/Q* is increasing) if the percentage increase in the output price is larger than the percentage increase in the electricity price. A higher increase in the output price gives incentives for higher production and hence, more energy use, while a higher increase in the energy price will lower the energy use. If output becomes relatively more valuable than electricity becomes costly, firms scale up production. As there are decreasing returns to scale, changes in energy use will be relatively higher than changes in production.

3. Application of the model to EU ETS

The motivation for the compensation scheme is that trade-exposed firms face higher electricity prices resulting from the carbon price signals created by the EU ETS (so-called "indirect emission costs").

To model this, let m denote the ETS price, and γ denote the electricity price increase per unit increase in the ETS price, i.e. $de = \gamma dm$.

We consider a compensation scheme with support equal to the maximum support allowed in line with the EU regulation (EU, 2020). Where electricity consumption efficiency benchmarks are applicable, the compensation is a subsidy (s) per unit actual output:

(7) $s = \theta m \mu \overline{ES}$,

where $\theta \leq 1$ is the support intensity,[9] $\overline{ES} = \overline{\left(E/Q \right)}$ is the electricity efficiency standard,[10] and μ is the CO_2 emissions factor applied in the relevant geographical area (tCO_2/MWh).[11]

Most PITE firms have significant emissions of CO_2. These emissions are typically a combination of output, input factors and production technologies. To simplify the analysis, we will assume that emissions can be assigned proportionally to either output, electricity use or capital (or other input factors) – which one is most relevant will depend on the production technology and typically vary across PITE sectors. One example of emissions proportional to output is emissions from the process industry (e.g., metals and minerals), where emissions occur from the process itself. This can be thought of as emissions proportional to A (the total factor productivity) in the model, and hence output. Some industries produce their own electricity, such as liquefied natural gas (LNG) facilities, and emissions can be proportional to other input factors used such as limestone in cement production or carbon nodes in aluminum production. Finally, for aluminum production the emissions factor, measured in CO_2-equivalents, also varies significantly according

[9] The maximum aid amount per beneficiary will be equal to 75% of the indirect emission costs incurred, EU (2020).
[10] Defined as product-specific electricity consumption per tonne of output achieved by the most electricity-efficient methods of production for the product considered, EU (2020), 15 (14).
[11] The CO_2 emissions factor can either be derived based on the "weighted average of the CO_2 intensity of electricity produced from fossil fuels", or "based on a study of the CO_2 content of the actual margin setting technology in the electricity market" (EU, 2020, 15, (10) and (11)). In the latter case (which, e.g., Norway has chosen, cf. Norwegian Environment Agency, 2025), we would have $\mu = \gamma$.

to the production technology used, see Fenhann (2000). This can also be interpreted as emissions proportional to production, as technology is partly captured by A.

Hence, we will consider the following three alternatives:

i) Emissions are expressed as a fixed factor of production ε_Q,

ii) Emissions are expressed as a fixed factor of electricity use, ε_E,

iii) Emissions are expressed as a fixed factor of capital ε_K,

where $\varepsilon_Q, \varepsilon_E, \varepsilon_K \geq 0$. The PITE firms typically also receive free emissions allowances, which in the EU ETS are based on ex-ante product-specific benchmarks of emissions per unit of production ($\bar{\varepsilon}_Q$).[12] This is the case irrespective of whether emissions are expressed as a fixed factor of output, electricity use or capital. We treat the CO_2 emissions price, *m*, as exogenous, which means that we disregard potential impacts on the emission price on the production decisions of the PITE firms. This is reasonable since use of the compensation scheme is decided at the national level (for selected industries), while the EU ETS covers many countries and more sectors (not least the electricity sector).

These simplifying assumptions imply that we can write the effective price of output in case i) as

(8) $p = \tilde{p} + s - m(\varepsilon_Q - \bar{\varepsilon}_Q)$,

where $\tilde{p}$ is the market price of Q net of the labor costs per unit production. We assume throughout that the market price $\tilde{p}$ is fixed and unaffected by the domestic policy, e.g., because the national PITE firms compete both with other European firms and in a global market (cf. the carbon leakage concern).

In the two other cases, we have that

(9) $p = \tilde{p} + s + m\bar{\varepsilon}_Q$

As seen, in all cases, the compensation works as an implicit production subsidy. Hence, the compensation amount is related to production of goods.

[12] Allocation of allowances are proportional to a firm's production in recent years. For instance, allocation of allowances in the years 2026-30 is proportional to the firm's activity level in 2019-2023. This is often referred to as output-based allocation (see e.g. Böhringer et al., 2017).

Further, in case ii), the effective price of electricity can be expressed by the price of electricity in the absence of EU ETS ($\tilde{e}$) plus the increased price of electricity following from the EU ETS (γm) plus the increased cost of emissions caused by electricity use ($\varepsilon_e m$):

$$(10)\ e = \tilde{e} + (\gamma + \varepsilon_E) m$$

Finally, in case iii), the effective price of capital can be expressed by the market price on capital plus the increased cost of emissions caused by capital use ($\varepsilon_K m$):

$$(11)\ k = \tilde{k} + \varepsilon_K m$$

To explore the impacts of the compensation scheme we derive the outcome of four scenarios, where all of them apart from Scenario 0, also include free emissions allowances:

Scenario 0: No EU ETS

Scenario 1: EU ETS, no compensation scheme

Scenario 2: EU ETS, compensation scheme without any investment requirements

Scenario 3: EU ETS, compensation conditional upon additional decarbonization investments (investment requirements) to reduce emissions or to increase energy efficiency

Scenario 0 (No EU ETS) is simply found by the outcome of the optimization problem (eq.(2)), where the prices are given by (8), (10) and (11) for $m = 0$, $s = 0$ and $\gamma = 0$, i.e., $p = \tilde{p}, e = \tilde{e}, k = \tilde{k}$ in all three alternatives, i) – iii).

4. Scenario 1: EU ETS with no compensation scheme

The outcome of Scenario 1 is found by the optimization problem (eq. (2)), where the prices in the different cases are given by (8)-(11) and $s = 0$. The total impacts of the ETS on the PITE firms come via three channels: i) the impact of the ETS on the electricity price (γ), ii) the impact on the net output price via the allocation of allowances ($\bar{\varepsilon}_Q$), and iii) the impact on the net output or input price via the ETS price (m) and the emissions factor of production or input (ε_j). For a firm with significant electricity use, but sufficiently low emissions and free allowances, the first channel will be dominating. To find the impact of the ETS via this electricity price channel, we derive how the variables change with an increase in e (caused by an exogenous increase in m). The signs of the impacts on E, K and Q are given by (4), and the impact on E/Q is given by (5). We see that E, K, Q and E/Q all decrease when only considering this first channel i).

In Appendix B we derive the full expressions for the effects on E, K, Q and E/Q, and show that the second channel above ($\bar{\varepsilon}_Q$) tends to increase all four variables, while the third channel tends to decrease them. In other words, if allocation of free allowances is sufficiently small, all four variables will decline as a result of the ETS. In the case where emissions are proportional to output, a sufficient (but not necessary) condition for E, K, Q and E/Q to decrease is that a firm's free allowances do not exceed its emissions.

We summarize this in the following proposition:

Proposition 1: *Without a compensation scheme, the EU ETS leads to lower production, lower use of both input factors, lower emissions and increases the electricity efficiency for the PITE firms as long as the free allowances are sufficiently low. In the case where emissions are proportional to output, a sufficient (but not necessary) condition for this to hold is that a firm's free allowances do not exceed its emissions. Another sufficient condition is that emissions and free allowances are both sufficiently small, so that the effect of the ETS via the electricity price (indirect emissions cost) dominates.*

Proof: See Appendix B.

Thus, the proposition indicates that the ETS may lead to reduced production, and hence a risk for carbon leakage, but also increased electricity efficiency, in line with the goals for the green transition. However, for a sufficiently large (over)allocation of free allowances, the conclusions of the proposition could be reversed, turning around both the leakage risk and the green transition.[13]

[13] According to Wettestad and Hagem (2024), the Swedish industry received more free allowances than their actual emissions for the period 2013-2020.

5. Scenario 2: EU ETS with compensation scheme

The outcome of the EU ETS *with the compensation scheme* is found by the optimization problem (eq. (2)), where the prices are given by (8)-(11). Let E^{S2}, K^{S2} and Q^{S2} denote the outcome of this optimization problem.

We first consider the direct effect of the compensation scheme (compared with Scenario 1), that is, the effects of implementing $s > 0$. This increases p (cf. (8) and (9)), and we see from (4) and (5) that Q, E, K and E/Q increase with p. Hence, the compensation scheme itself (as defined above) leads to higher production, and hence potential for reduced carbon leakages, but it also reduces the electricity efficiency and increases the emissions of the sector, which goes against the goals of the green transition.

We will now derive the net impact of the EU ETS with the compensation scheme, i.e., the simultaneous effect of both shifts. Thus, we study how the EU ETS with the compensation scheme performs compared to no climate policy (that is, compared to Scenario 0).

5.1. No emissions and no free allowances

We start with the case where there are no emissions associated with the production; $\varepsilon_Q, \varepsilon_E, \varepsilon_K =$ 0, and there are no free allowances ($\bar{\varepsilon}_Q = 0$), which means that $dp = ds = \theta\mu\overline{ES}dm$, $de = \gamma dm$ and $dk = 0$. This case is justified by the fact that the compensation scheme is independent of the emissions for the industries that are included in the scheme – the scheme is targeting *electricity*-intensive industries.

We then find the following effects (cf. Appendix C):

$$
(12)\quad
\begin{aligned}
dE^{S2} &\equiv E^{S2} - E^{S0} = \frac{1}{N}\frac{\beta Q}{K^2}\left[-\gamma(1-\beta) + \alpha\frac{\overline{ES}}{ES}\theta\mu\right]m \\
dK^{S2} &\equiv K^{S2} - K^{S0} = \frac{1}{N}\frac{\alpha\beta Q}{EK}\left(-\gamma + \frac{\overline{ES}}{ES}\theta\mu\right)m \\
dQ^{S2} &\equiv Q^{S2} - Q^{S0} = \frac{1}{N}\frac{Q^2\alpha\beta}{EK^2}\left[-\gamma + \frac{\overline{ES}}{ES}(\alpha+\beta)\theta\mu\right]m \\
d\left(E/Q\right)^{S2} &\equiv \left(E/Q\right)^{S2} - \left(E/Q\right)^{S0} = \frac{1}{e}\left[\theta\mu\alpha\overline{ES} - \gamma ES\right]m
\end{aligned}
$$

where $ES = E/Q$ is the electricity intensity of the beneficiary firm. We find that:

$$
(13)\quad
\begin{aligned}
&dE^{S2} > 0 \text{ iff } \theta \frac{\mu}{\gamma}\frac{\overline{ES}}{ES} > \frac{1-\beta}{\alpha} > 1 \\
&dK^{S2} > 0 \text{ iff } \theta \frac{\mu}{\gamma}\frac{\overline{ES}}{ES} > 1 \\
&dQ^{S2} > 0 \text{ iff } \theta \frac{\mu}{\gamma}\frac{\overline{ES}}{ES} > \frac{1}{\alpha+\beta} > 1 \\
&d\left(E/Q\right)^{S2} > 0 \text{ iff } \theta \frac{\mu}{\gamma}\frac{\overline{ES}}{ES} > \frac{1}{\alpha} > 1
\end{aligned}
$$

Since $\alpha+\beta<1$ and the support intensity is less than one in the EU ETS (θ = 0.75), *dE*, *dK*, *dQ* and *d(E/Q)* can only be positive for $\frac{\mu}{\gamma}\frac{\overline{ES}}{ES}$ sufficiently larger than 1. Further, if $\mu \le \gamma$ (cf. footnote 11), the net effects on all four variables are negative unless the electricity intensity of the beneficiary (*ES*) is notably smaller than the standard ($\overline{ES}$). For very electricity efficient firms, however, the effects may be turned around. For the effects on electricity efficiency, we know from (6) that it boils down to whether the percentage increase in the net price on output (due to the compensation scheme) is higher or lower than the percentage increase in the electricity price (caused by the ETS). If the output price increases relatively more, electricity intensity *increases*.

From (13), we can also see that the compensation scheme can give overcompensation. Overcompensation occurs if $sQ > \gamma mE$, i.e., if the total subsidy received is larger than the increased total costs the firm gets due to the EU ETS market. Inserting equation (7) into this condition, we derive the condition $\theta \frac{\mu}{\gamma}\frac{\overline{ES}}{ES} > 1$. Thus, the discussion above also shows that overcompensation may occur for particularly electricity efficient firms, and/or for large discrepancies between estimated and actual electricity price increase following from EU-ETS ($\mu > \gamma$).

This gives the following Proposition:

Proposition 2: *Assume that the EU ETS is introduced with a compensation scheme based on an electricity efficiency standard. Also assume that there are no emissions associated with production for the firm receiving the compensation, and there are no free allocations of permits. Then for firms that are sufficiently electricity efficient (relative to the efficiency standard), the compensation scheme may lead to larger production and electricity input and lower electricity efficiency than prior to the EU ETS. This depends, however, also on the support intensity and the* *emissions factor of the grid used in the compensation scheme relative to the ETS' impact on the electricity price. Overcompensation may also occur for very electricity efficient firms or if there is a large discrepancy between the estimated and actual electricity price.*

Proof: See Appendix C and equation (13).

To further interpret the results, we know that the support intensity θ is set to less than one (0.75 , see footnote 9). Also, the efficiency standard (or benchmark) $\overline{ES}$ in the EU ETS is product-specific and was set in 2020 based on the most electricity efficient production methods (EU, 2020), see footnote 10 . It is set for the fourth phase of the EU ETS, i.e., the period 2021-2030, and reduced by 1.09 % on an annual basis[14]. However, we cannot rule out that firms during this decade invest in new production technologies implying that their electricity intensity becomes sufficiently below the standard decided in 2020. For instance, there may be technological developments that go substantially beyond "state of the art" in 2020.[15]

Further, the impacts of the ETS on the electricity price are complex and might be lower than reflected by the applied emissions factor of the grid (i.e., we might have $\mu > \gamma$). For instance, there are more than one bidding zone in several European countries, whereas the emissions factor μ is held constant within a country. The impacts of EU ETS on the electricity prices typically vary across bidding zones, depending on inter alia the share of renewables.[16]

A main finding in Proposition 2 is that the electricity intensity in the PITE firms may increase as a result of an ETS combined with a compensation scheme – that is, compared to a situation with no climate policy. This is the case if a firm is very energy efficient initially, even compared to the standard (as explained above). The intuition for this result is that the compensation scheme itself stimulates output via higher net price on output. Due to decreasing returns to scale (

[14] EU (2021).

[15] For instance, Hydro is testing a new technology which they hope will reduce energy consumption to 11.5 kWh per kilo of aluminum. The present standard in the compensation scheme is 13.45 kWh (2024). See EU (2021) and Hydro (2019).

[16] In Norway, there are five bidding zones. The emissions factor of the grid, μ, is set to 0.53 (Norwegian Environment Agency, 2025), slightly higher than the emissions factor of a typical gas power plant. Electricity prices in the two northern bidding zones in Norway are only slightly affected by electricity prices in other countries, and with hardly any fossil power plants in Norway, γ is most likely far below μ in these two bidding zones. Multiplying the emissions factor μ = 0.53 with the average EU ETS price in 2024 (67 euro/tCO2) should imply an *increase* in the Norwegian electricity price of 36 euro/MWh (due to the ETS). As a comparison, the electricity prices in the two northern bidding zones in Norway were 28 and 23 euro/MWh, respectively (https://data.nordpoolgroup.com/auction/day-ahead/prices).

$\alpha+\beta<1$),[17] this implies that both inputs (*E* and *K*) increase proportionally more than output, implying higher electricity intensity. On the other hand, the higher cost of electricity (due to the ETS) reduces the use of electricity in production. However, if electricity use is relatively low, this last effect is less important and outweighed by the former effect. In that case, the net effect of the ETS with compensation scheme is to incentivize lower electricity efficiency than in the absence of EU ETS.

5.2. Including emissions and free allowances

In the discussion above (and the derivations leading up to Proposition 2), we assumed that $\varepsilon_Q,\varepsilon_E,\varepsilon_K=0$ and $\bar{\varepsilon}_Q=0$. We now look at the case where these variables are positive. In Appendix D we derive updated expressions for how the variables change from Scenario 0 (no climate policy) to Scenario 2 (ETS with compensation scheme). Based on these, we find:

$$
\begin{aligned}
& dE^{S2}>0 \text{ iff } \frac{\overline{ES}}{ES}\frac{\theta\mu+\frac{1}{\overline{ES}}\left(\bar{\varepsilon}_Q-\varepsilon_Q-\frac{K}{Q}\varepsilon_K\right)}{\gamma+\varepsilon_E}>\frac{1-\beta}{\alpha}>1\\
& dK^{S2}>0 \text{ iff } \frac{\overline{ES}}{ES}\frac{\theta\mu+\frac{1}{\overline{ES}}\left(\bar{\varepsilon}_Q-\varepsilon_Q-\frac{1-\alpha}{\beta}\frac{K}{Q}\varepsilon_K\right)}{\gamma+\varepsilon_E}>1\\
& dQ^{S2}>0 \text{ iff } \frac{\overline{ES}}{ES}\frac{\theta\mu+\frac{1}{\overline{ES}}\left(\bar{\varepsilon}_Q-\varepsilon_Q-\frac{1}{\alpha+\beta}\frac{K}{Q}\varepsilon_K\right)}{\gamma+\varepsilon_E}>\frac{1}{\alpha+\beta}>1\\
& d\left(E/Q\right)^{S2}>0 \text{ iff } \frac{\theta\mu\overline{ES}+\left(\bar{\varepsilon}_Q-\varepsilon_Q\right)}{(\gamma+\varepsilon_E)ES}>\frac{1}{\alpha}>1.
\end{aligned}
\tag{14}
$$

Comparing these new expressions with the corresponding ones in equation (13) (i.e., for firms with no emissions), we see that the likelihood of *dE*, *dK dQ* and *d(E/Q)* being positive may either increase or decrease. The emissions factors of production or input factor all reduce the expressions on the left-hand side of the inequality, implying that it is less likely that the variables increase. On the other hand, free allowances have the opposite effects. If emissions are proportional to output (Case i)), and free allowances only cover a subset of emissions ($\bar{\varepsilon}_Q<\varepsilon_Q$), then it is more likely than before that both electricity, output and electricity intensity decline

[17] The conclusion may be reversed for increasing returns to scale. However, this is hardly the case in the long run or if the firm is a price taker as we assume. Also, the second order condition for profit maximization will not be met, see Appendix A.

compared to Scenario 0. The effective price of output decreases (compared to $\varepsilon_Q, \varepsilon_E, \varepsilon_K, \bar{\varepsilon}_Q = 0$), see (8), and thus increases the likelihood of *E/Q* decreasing. This gives the following result:[18]

Proposition 3: *Assume that the EU ETS is introduced with a compensation scheme based on an electricity efficiency standard. If there are emissions linked to output, and the free allowances are less than these emissions, it is more likely that electricity efficiency is higher and emissions lower with EU ETS and compensation scheme than without EU ETS – compared with a firm that has no emissions. The opposite result follows if the free allowances are higher than emissions and emissions are linked to output.*

Proof: See Appendix D and equation (14).

5.3. Numerical simulations

As the results of introducing the compensation scheme had indeterministic effects on the variables in the model when we compare to no climate policy, we introduce numerical simulations based on equation (1), where we use the aluminum production in Norway as an example. Table 1 shows the parameter values from the calibration. See Appendix F for more information.

Table 1 Calibrated parameter values for Norwegian aluminum production

Parameter	Value	Unit
p	2000	euro / ton aluminum
e	54	euro / MWh
α	0.36	
β	0.36	
μ	0.53	tCO_2/MWh
γ	0.53	tCO_2/MWh
θ	0.75	

[18] In the other cases (ii) and iii)), the results depend on both $\bar{\varepsilon}_Q$ and $\varepsilon_{j,\ j=E,K}$, and it is less intuitive to interpret the results.

ε_Q	1.75	ton CO_2 / ton aluminum
$\overline{\varepsilon}_Q$	1.65	ton CO_2 / ton aluminum
ES	13.5	MWh / ton aluminum
$\overline{ES}$	13.45	MWh / ton aluminum

We focus on the effects on the energy efficiency conditions in equations (13) and (14). In the case with no emissions and no free allowances (equation (13)), we find that $\theta \frac{\mu}{\gamma} \frac{\overline{ES}}{ES} = 0.75$ and $\frac{1}{\alpha} = 2.74$. Thus, in this case $d\left(E/Q\right)^{S2} < 0$. This means that energy efficiency increases when the compensation scheme is introduced for firms with no emissions and no free allowances, compared to the situation with no climate policies. Note that in this numerical example, $\frac{\mu}{\gamma} = 1$. For energy efficiency to be reduced, we find that $\frac{\mu}{\gamma} > 3.67$, i.e., the CO_2 emissions factor of the grid in the geographical area must be almost four times higher than the actual electricity price increase from an increase in EU ETS price in the same area.

Norway has five bidding zones for electricity, see footnote 19, with the electricity prices in the two Northern zones only slightly affected by electricity prices in other countries. As mentioned in the footnote, the electricity prices in these zones are significantly lower than even the expected increase in the Norwegian electricity price due to ETS. Thus, in geographical areas like these, one would expect reduced energy efficiency from the climate policy with the compensation scheme when there are no emissions and no free allowances.

We now move to the case where we introduce free allowances and concentrate on the alternative where emissions follow from production ($\varepsilon_Q > 0$). From equation (14), we find that $\theta \frac{\mu}{\gamma} \frac{\overline{ES}}{ES} = 0.73$. Thus, based on our calibration, this increases the likelihood of increased energy efficiency from the introduction of EU-ETS with the compensation scheme.

6. Scenario 3. Compensation scheme with investment obligations

The revised EU ETS guidelines make the compensation conditional upon additional efforts by the firms concerned, such as complying with the recommended electricity efficiency or by investing a significant share of at least 50 % of the aid amount in projects that lead to substantial reductions of the installation's greenhouse gas emissions (EU, 2020).[19]

6.1. Investments in emission reduction technologies

We first consider the case where the beneficiaries must spend a share of the aid on emission reduction technologies.

To simplify the analysis, we assume that the investment in the emission reduction technologies removes the emissions, linked to either *Q*, *E* or *K,* completely. That is, either ε_Q , ε_E or ε_K is reduced from a strictly positive number to zero (cf. the three alternative cases put forward in Section 3).[20] Furthermore, we assume that this investment[21] does not affect the optimal choice of input and output levels, except via potential changes in the effective prices of inputs and output as the effective prices depend on the emissions factors (see equations (8)-(11)).

For the investment requirement to be binding, i.e., such that it would not happen without the requirement, we must have that the costs of investment, *I*,[22] are larger than the reduced emission costs:

$$
(15)\quad
\begin{aligned}
I_Q &> m\varepsilon_Q Q \\
I_E &> m\varepsilon_E E \\
I_K &> m\varepsilon_K K
\end{aligned}
$$

Hence, a firm does not implement this investment unless it is more profitable to invest and receive compensation than not receiving any compensation. This also means that the required

---

[19] Norway has introduced a share of at least 40% to be spent on climate or energy efficiency measures. It has also introduced a cap on total payments for compensation in a calendar year (7 billion NOK), ESA (2024), see also the introduction.

[20] Note that $\bar{\varepsilon}_Q$ is not affected by the investments, as the firm receives free allowances in proportion to its production level, even if its emissions are reduced to zero (in line with EU ETS regulations as described above).

[21] The type of investments depends on the whether the emissions are linked to *Q*, *E* or *K*. Examples may be switching to renewable energy, carbon capture and storage, investing in new capital equipment etc.

[22] We assume that this cost satisfies the requirement that a given share of the aid is spent on emissions mitigation efforts, i.e., $I_j \geq \kappa s Q$, where κ is the required share.

investments are not socially efficient (given the compensation scheme, and assuming that the ETS price is set optimally). The cost of the investment exceeds the benefits and must be subsidized to be implemented.

In the following, we compare Scenarios 3 and 2 as well as Scenarios 3 and 1, to examine the effects of the additional decarbonization requirement. This means that we compare the compensation scheme with obligations to no such obligations, as well to no compensation scheme.[23]

Case i). Reducing ε_Q **to zero:**

Consider the case where $\varepsilon_Q > 0$ and that it can be reduced to zero by investments in a new emission free technology at cost I_Q.

We start by comparing Scenarios 3 with Scenario 2. In this case, this implies that the difference between the effective price of output with investments (p^{S3}) and the effective price of output in the absence of investment requirements as in Scenario 2 (p^{S2}) is (since allocated allowances are unchanged):

(16) $p^{S3} - p^{S2} = m\varepsilon_Q > 0$

The effective prices on electricity and capital are unchanged.

If a firm implements the investment and gets full compensation, it is optimal for the firm to increase production since the effective price of output increases. Let $\Delta\Pi_Q$ denote the change in profit from the investment. It is profitable for the firm to implement the investment and receive full compensation, compared to no compensation, if and only if:

(17) $\Delta\Pi_Q > I_Q$

[23] If emissions are reduced to zero, the firm may no longer receive free allowances from 2026. This follows from new EU rules that excludes free allowances if emissions are low, and if they combust more than 95 percent biomass. There is an ongoing discussion in Norway about the wood processing company Norsk Skog due to this. If firms lose their free emissions, the incentive for decarbonization will be reduced even if they will receive compensation. This is not taken into account in the analysis below.

This means that for a range of investment costs given by $\Delta\Pi_Q > I_Q > m\varepsilon_Q Q^{S2}$, it is optimal to implement the investment that was not optimal without the investment requirement.[24]

Since the effective output price is increased, while the input prices are unchanged, we know from before (equations (4)-(6)) that this will lead to higher production, more use of both input factors, and reduced electricity efficiency.

Another relevant comparison is between Scenario 3 with Scenario 1, as not meeting the criteria will give no subsidy. This gives the following increase in the effective price with investment:

(18) $p^{S3} - p^{S1} = s + m\varepsilon_Q > 0$

As seen, the price increase is even higher than when comparing to Scenario 2.

We get similar results as when we compared to Scenario 2, with higher production, more use of both input factors, and reduced electricity efficiency, given that the increase in profits is higher than the investment cost.

Case ii). Reducing ε_E to zero:

Now, assume that we have $\varepsilon_E > 0$ without investments, but ε_E will be reduced to 0 with decarbonization investments.

We first compare Scenarios 3 with Scenario 2. If the investment is implemented, the effective prices of output and capital are not affected. Hower, the effective price of electricity has decreased:

(19) $e^{S3} - e^{S2} = -m\varepsilon_E < 0$

It is profitable for firms to implement the investment and receive full compensation, compared to no compensation, if the change in their profit from doing so is higher than the investment cost, i.e.,

[24] Note that if emissions are not reduced to zero with the investment, the incentive to invest and receive full compensation will be lower as the firm still has to pay for the residual emissions.

(20) $\Delta\Pi_E > I_E$.

This means that for a range of investment costs given by $\Delta\Pi_E > I_E > m\varepsilon_E E^{S2}$, it is optimal for the firm to implement the investment, which was not optimal without the requirement.

Since the effective electricity price is reduced while other prices are unchanged, it follows again that output and the use of input factors increase whereas electricity efficiency is reduced.

Comparing Scenario 3 with Scenario 1 gives the same change in the electricity price as when compared to Scenario 2. Thus, the conclusions are similar.[25]

Case iii). Reducing ε_K to zero**:**

We now consider the case where $\varepsilon_K > 0$, and that it can be reduced to zero by an investment in new technologies. If the investment is implemented, the effective prices of output and electricity are not affected compared with Scenario 2. Hower, the effective price of capital has decreased:

(21) $k^{S3} - k^{S2} = -m\varepsilon_k < 0$

As before, it is profitable for the firm to implement the investment and receive full compensation, compared to no compensation, if the profit increase by doing so is higher than the investment cost:

(22) $\Delta\Pi_K > I_K$

Thus, for a range of investment costs given by $\Delta\Pi_K > I_K > m\varepsilon_K K^{S2}$, it is optimal for the firm to implement the investment, which was not optimal without the investment requirement.

Since effective prices of output and electricity are unchanged, electricity efficiency is now also unchanged, see (3). Output increases, however, since the effective price of capital has decreased. This also increases the use of both electricity and capital, see (4).

Comparing Scenario 3 with Scenario 1 gives an equal change in the price of capital as above, and the results are therefore similar to the comparison with Scenario 2.

---

[25] Note that the change in profits may be different. This is also true for the similar comparison in Case iii) below.

To summarize, we have the following results:

Proposition 4: *If emissions are proportional with output (Q) or electricity (E) use, and compensation with decarbonization requirements is introduced, we get higher production, lower emissions and reduced electricity efficiency compared to compensation without such requirements as well as compared to no compensation. If emissions are instead proportional with capital (K), the effects are higher production, lower emissions and unchanged electricity efficiency.*

Proof: See the discussion above.

6.2. Investments in energy efficiency

Consider now instead that compensation is dependent on an investment with cost I in a new technology that increases energy efficiency. In our model, we can make energy more productive in two different ways, see equation (1). First, by increasing the total factor productivity, A, and second, by increasing the output elasticity of electricity, α. In the first case, both input factors become more productive, while in the second case, only electricity becomes more productive. We assume that $\alpha + \beta < 1$ still holds in the latter case.

Consider the optimal condition for energy efficiency given by equation (3). i.e., $\frac{E}{Q} = \frac{p\alpha}{e}$. As we see, an increase in the total factor productivity A due to a technology investment, does not have any impact on energy efficiency. An increase in A will have a direct negative effect on the use of energy (E), as less energy is needed to provide the same energy service and hence production as before. However, it will also have an indirect (rebound) positive effect due to higher productivity. With the Cobb Douglas production function, the rebound effect will completely offset the direct negative impact on energy use. Thus, energy and output will increase proportionally, and the energy efficiency will not change. Hence, this type of investment would not be implemented for the purpose of meeting the energy efficiency requirements for subsidies.

As we also see from equation (3), energy efficiency can only increase if the output elasticity of electricity is reduced for given prices (p and e), i.e., energy becomes less productive. A decrease in the output elasticity implies that more energy is needed to provide the production as before. This will have a direct negative impact on energy use. But we also get a rebound effect as discussed above. Output will decrease, but less than the energy use, as the output factor of electricity is less than one ($\alpha < 1$).

Based on the discussion above, we can outline the following proposition:[26]

Proposition 5: *If compensation with energy efficiency requirements is introduced, it will incentivize investments which leads to lower electricity productivity, compared to compensation without such requirements.*

Proof: See the discussion above and Appendix E.

[26] This result clearly hinges on the assumed production technology. However, the fact that energy efficiency improvements typically lead to some rebound effect has long been understood (see e.g. Gillingham et al., 2016; Böhringer and Rivers, 2021). The extent of rebound is an open question, though, and will typically be context and sector dependent. When the energy efficiency improvement leads to *higher* energy use, it is often referred to as a backfire.

7. Conclusions

The purpose of this paper is to shed some light on the properties of the compensations scheme for indirect carbon costs. EU firms face higher electricity prices resulting from the price signals created by the EU ETS. The purpose of the compensation scheme is to alleviate the competitive disadvantage with respect to firms operating outside of the EU. By employing a standard Cobb-Douglas production function we derive some general analytical results.

We find that the compensation scheme leads to higher production, and hence potentially reduced carbon leakage, compared to EU ETS without compensation, but it also reduces the electricity efficiency of production and increases emissions in the PITE firms compared to no compensation, which go against the goals of the green transition. If we compare to no climate policy at all, the EU ETS with the compensation scheme may still do worse when it comes to emissions and energy efficiency for the PITE firms, but this depends on the effects on the electricity prices in the geographical areas. Increased emissions from the PITE industry must be compensated by lower emissions from other sectors to meet the targets within EU ETS.

The guidelines for the compensation scheme are designed to avoid overcompensation compared to a situation before the EU ETS. However, we cannot rule out that the scheme compensates more than the actual indirect cost for some sectors/firms.

In the main revision of the guidelines (EU, 2020), the compensation was made conditional upon additional emission reduction and energy efficiency measures by the firms concerned. Binding decarbonization constraints imply that firms are incentivized to implement socially inefficient abatement efforts, assuming that the ETS price is at an optimal level. Furthermore, these investments may also decrease electricity efficiency. Moreover, if compensation with energy efficiency requirements is introduced, it will incentivize investments which lead to lower electricity productivity.

To sum up, our study shows that introducing the compensation scheme in EU ETS is suboptimal if the aim is to reduce the emissions cost-effectively. Thus, using compensation to reduce carbon leakage comes at a cost. However, this may still be a preferred arrangement if policy makers are concerned about employment in the PITE industry or global emission reductions. The latter may be the case if carbon leakage significantly offsets emission reductions in EU ETS. However, attempts to reduce the costs of the compensation scheme by introducing investments obligations may make things worse by incentivizing suboptimal investments and worsen electricity efficiency.

Our results have been derived using a stylized Cobb Douglas production function. A relevant extension of our analysis could be to consider a different production function, such as a CES (Constant Elasticity of Substitution) production function. Still, we believe that the analytical results we have derived reflect some general mechanisms and thus should be taken into consideration.

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Appendix A

1.o.c of the maximization problem given by (2) are given by

$$pf'_E = e$$
$$pf'_K = k$$

which gives:

$$E = \frac{pQ\alpha}{e}, \quad K = \frac{pQ\beta}{k}$$

Total differentiating the first order conditions (given (1)):

$$pf''_{EE} \cdot dE + pf''_{EK} \cdot dK = de - f'_E \cdot dp$$
$$pf''_{KE} \cdot dE + pf''_{KK} \cdot dK = dk - f'_K \cdot dp$$

We find that

$$\frac{dE}{de} = \frac{f''_{KK}}{N} < 0, \quad \frac{dE}{dk} = \frac{-f''_{EK}}{N} < 0, \quad \frac{dE}{dp} = \frac{\left[f'_K f''_{EK} - f'_E f''_{KK}\right]}{N} > 0$$
$$\frac{dK}{de} = \frac{-f''_{KE}}{N} < 0, \quad \frac{dK}{dk} = \frac{f''_{EE}}{N} < 0, \quad \frac{dK}{dp} = \frac{\left[f'_E f''_{EK} - f'_K f''_{EE}\right]}{N} > 0$$
$$where$$
$$N = p\left[f''_{EE} \cdot f''_{KK}) - (f''_{EK})^2\right] > 0$$

furthermore:

$$\frac{dQ}{de} = f'_E \frac{dE}{de} + f'_K \frac{dK}{de}$$

$$\frac{dQ}{dk} = f'_E \frac{dE}{dk} + f'_K \frac{dK}{dk}$$

$$\frac{dQ}{dp} = f'_E \frac{dE}{dp} + f'_K \frac{dK}{dp}$$

From (1), we find:

$$f'_E = \frac{\alpha Q}{E} > 0, \quad f'_K = \frac{\beta Q}{K} > 0$$

$$f''_{EE} = \frac{\alpha(\alpha-1)Q}{E^2} < 0$$

$$f''_{KK} = \frac{\beta(\beta-1)Q}{K^2} < 0$$

$$f''_{EK} = \frac{\alpha\beta Q}{EK} > 0$$

$$f''_{EE} \cdot f''_{KK} - (f''_{EK})^2 = \alpha\beta \frac{Q^2}{E^2K^2}\left(1-\alpha-\beta\right) > 0$$

$$\frac{dE}{de} = \frac{1}{N}\frac{\beta(\beta-1)Q}{K^2} < 0$$

$$\frac{dE}{dk} = -\frac{1}{N}\frac{\alpha\beta Q}{EK} < 0$$

$$\frac{dE}{dp} = \frac{1}{N}\frac{\alpha\beta Q^2}{EK^2} > 0$$

$$\frac{dK}{de} = -\frac{1}{N}\frac{\alpha\beta Q}{EK} < 0$$

$$\frac{dK}{dk} = \frac{1}{N}\frac{\alpha(\alpha-1)Q}{E^2} < 0$$

$$\frac{dK}{dp} = \frac{1}{N}\frac{\alpha\beta Q^2}{E^2K} > 0$$

$$\frac{dQ}{de} = \frac{Q\alpha}{E}\frac{dE}{de} + \frac{Q\beta}{K}\frac{dK}{de} = \frac{1}{N}\left[\frac{Q\alpha}{E}\frac{\beta(\beta-1)Q}{K^2} - \frac{Q\beta}{K}\frac{\alpha\beta Q}{EK}\right]$$

$$= \frac{1}{N}\frac{Q^2\alpha\beta}{EK^2}\left[\beta-1-\beta\right] = -\frac{1}{N}\frac{Q^2\alpha\beta}{EK^2} < 0$$

$$\frac{dQ}{dk} = \frac{Q\alpha}{E}\frac{dE}{dk} + \frac{Q\beta}{K}\frac{dK}{dk} = \frac{Q\alpha}{E}\left(-\frac{p}{N}\frac{\alpha\beta Q}{EK}\right) + \frac{Q\beta}{K}\left(\frac{p}{N}\frac{\alpha(\alpha-1)Q}{E^2}\right)$$

$$= \frac{1}{N}\frac{Q^2\alpha\beta}{E^2K}\left[-\alpha+\alpha-1\right] = -\frac{1}{N}\frac{Q^2\alpha\beta}{E^2K} < 0$$

$$\frac{dQ}{dp} = \frac{Q\alpha}{E}\frac{dE}{dp} + \frac{Q\beta}{K}\frac{dK}{dp} = \frac{1}{N}\left[\frac{Q\alpha}{E}\frac{\alpha\beta Q^2}{EK^2} + \frac{Q\beta}{K}\frac{\alpha\beta Q^2}{E^2K}\right]$$

$$= \frac{1}{N}\frac{\alpha\beta Q^3}{E^2K^2}(\alpha+\beta) > 0$$

Appendix B

Here we compare scenario 1 with scenario 0, that is, we differentiate the variables *E, K* and *Q* with respect to *m*, and then use the expressions in Appendix A. We include all three alternatives of ε_j in the derivations:

$$\frac{dE}{dm}=\frac{dE}{de}\frac{de}{dm}+\frac{dE}{dk}\frac{dk}{dm}+\frac{dE}{dp}\frac{dp}{dm}$$
$$=-\frac{1}{N}\frac{\beta(1-\beta)Q}{K^2}(\gamma+\varepsilon_E)-\frac{1}{N}\frac{\alpha\beta Q}{EK}\varepsilon_k+\frac{1}{N}\frac{\alpha\beta Q^2}{EK^2}\left(\bar{\varepsilon}_Q-\varepsilon_Q\right)$$
$$=\frac{1}{N}\frac{\beta Q}{EK^2}\left[-(1-\beta)E(\gamma+\varepsilon_E)-\alpha K\varepsilon_k+\alpha Q\left(\bar{\varepsilon}_Q-\varepsilon_Q\right)\right]$$

$$\frac{dK}{dm}=\frac{dK}{de}\frac{de}{dm}+\frac{dK}{dk}\frac{dk}{dm}+\frac{dK}{dp}\frac{dp}{dm}$$
$$=-\frac{1}{N}\frac{\alpha\beta Q}{EK}(\gamma+\varepsilon_E)-\frac{1}{N}\frac{\alpha(1-\alpha)Q}{E^2}\varepsilon_K+\frac{1}{N}\frac{\alpha\beta Q^2}{E^2K}\left(\bar{\varepsilon}_Q-\varepsilon_Q\right)$$
$$=\frac{1}{N}\frac{\alpha Q}{E^2K}\left[-\beta E(\gamma+\varepsilon_E)-(1-\alpha)K\varepsilon_K+\beta Q\left(\bar{\varepsilon}_Q-\varepsilon_Q\right)\right]$$

$$\frac{dQ}{dm}=\frac{dQ}{de}\frac{de}{dm}+\frac{dQ}{dk}\frac{dk}{dm}+\frac{dQ}{dp}\frac{dp}{dm}$$
$$=-\frac{1}{N}\frac{Q^2\alpha\beta}{EK^2}(\gamma+\varepsilon_E)-\frac{1}{N}\frac{Q^2\alpha\beta}{E^2K}\varepsilon_K+\frac{1}{N}\frac{\alpha\beta Q^3}{E^2K^2}(\alpha+\beta)\left(\bar{\varepsilon}_Q-\varepsilon_Q\right)$$
$$=\frac{1}{N}\frac{Q^2\alpha\beta}{E^2K^2}\left[-E(\gamma+\varepsilon_E)-K\varepsilon_K+Q(\alpha+\beta)\left(\bar{\varepsilon}_Q-\varepsilon_Q\right)\right]$$

$$\frac{d(E/Q)}{dm}=\frac{\alpha}{e}\frac{dp}{dm}-\frac{\alpha p}{e^2}\frac{de}{dm}$$
$$=\frac{1}{e}\left[\alpha(\bar{\varepsilon}_Q-\varepsilon_Q)-\frac{E}{Q}(\gamma+\varepsilon_E)\right]$$

We see that for both *E*, *K*, *Q* and *E/Q*, the expressions are negative if the output-based allocation of allowances ($\bar{\varepsilon}_Q$) is sufficiently low. More precisely:

$$\frac{dE}{dm}<0 \text{ iff } \bar{\varepsilon}_Q<\varepsilon_Q+\frac{(1-\beta)E}{\alpha Q}(\gamma+\varepsilon_E)+\frac{K}{Q}\varepsilon_K$$

$$\frac{dK}{dm}<0 \text{ iff } \bar{\varepsilon}_Q<\varepsilon_Q+\frac{E}{Q}(\gamma+\varepsilon_E)+\frac{(1-\alpha)K}{\beta Q}\varepsilon_K$$

$$\frac{dQ}{dm} < 0 \text{ iff } \bar{\varepsilon}_Q < \varepsilon_Q + \frac{E}{Q(\alpha+\beta)}(\gamma+\varepsilon_E) + \frac{K}{Q(\alpha+\beta)}\varepsilon_K$$

$$\frac{d(E/Q)}{dm} < 0 \text{ iff } \bar{\varepsilon}_Q < \varepsilon_Q + \frac{E}{\alpha Q}(\gamma+\varepsilon_e)$$

where γ captures the first channel (via the electricity price) discussed in the main text. In all four cases, the expressions are negative at least if emissions are proportional to output and the emissions factor of production is not lower than the output-based allocation rate (so that the firm does not get more allowances than it needs to cover its emissions). If emissions are not proportional to output, but rather to electricity or capital use, then the assessment depends on both the emissions coefficient and the value shares of electricity and capital (in addition to the effect on the electricity price via γ).

Appendix C

Here we derive the effects of EU ETS with the compensation scheme (Scenario 2) for a firm with no emissions (or free allowances). We use the expressions in Appendix A combined with the effects on the two prices as described in the main text:

$$\frac{dE^{S2}}{dm} = \frac{dE}{de}\frac{de^{S2}}{dm} + \frac{dE}{dp}\frac{dp^{S2}}{dm}$$
$$= -\frac{1}{N}\frac{\beta(1-\beta)Q}{K^2}\gamma + \frac{1}{N}\frac{\alpha\beta Q^2}{EK^2}\theta\mu\overline{ES} = \frac{1}{N}\frac{\beta Q}{K^2}\left[-\gamma(1-\beta) + \alpha\frac{\overline{ES}}{ES}\theta\mu\right]$$

$$\frac{dK^{S2}}{dm} = \frac{dK}{de}\frac{de^{S2}}{dm} + \frac{dK}{dp}\frac{dp^{S2}}{dm}$$
$$= -\frac{1}{N}\frac{\alpha\beta Q}{EK}\gamma + \frac{1}{N}\frac{\alpha\beta Q^2}{E^2K}\theta\mu\overline{ES} = \frac{1}{N}\frac{\alpha\beta Q}{EK}(-\gamma + \frac{\overline{ES}}{ES}\theta\mu)$$

$$\frac{dQ^{S2}}{dm} = \frac{dQ}{de}\frac{de^{S2}}{dm} + \frac{dQ}{dp}\frac{dp^{S2}}{dm}$$
$$= -\frac{1}{N}\frac{Q^2\alpha\beta}{EK^2}\gamma + \frac{1}{N}\frac{\alpha\beta Q^3}{E^2K^2}(\alpha+\beta)\theta\mu\overline{ES} = \frac{1}{N}\frac{Q^2\alpha\beta}{EK^2}\left[-\gamma + \frac{\overline{ES}}{ES}(\alpha+\beta)\theta\mu\right]$$

Using (5), $dp^{S2} = \theta\mu\overline{ES}dm$ and $de^{S2} = \gamma dm$ as outlined in section 5, we find

$$\frac{d\left(E/Q\right)}{dm} = \frac{\alpha}{e}\frac{dp^{S2}}{dm} - \frac{\alpha p}{e^2}\frac{de^{S2}}{dm} = \frac{\alpha}{e}\left[\theta\mu\overline{ES} - \frac{p}{e}\gamma\right] = \frac{1}{e}\left[\theta\mu\alpha\overline{ES} - \gamma ES\right]$$

Appendix D

Here we derive the effects of EU ETS with compensation scheme (Scenario 2) where we also account for possible emissions and free allowances.

$$\frac{dE^{S2}}{dm}=\frac{dE}{de}\frac{de^{S2}}{dm}+\frac{dE}{dk}\frac{dk^{S2}}{dm}+\frac{dE}{dp}\frac{dp^{S2}}{dm}$$
$$=-\frac{1}{N}\frac{\beta(1-\beta)Q}{K^2}(\gamma+\varepsilon_E)-\frac{1}{N}\frac{\alpha\beta Q}{EK}\varepsilon_K+\frac{1}{N}\frac{\alpha\beta Q^2}{EK^2}\left(\theta\mu\overline{ES}+\bar{\varepsilon}_Q-\varepsilon_Q\right)$$
$$=\frac{1}{N}\frac{\beta Q}{K^2}\left[-(1-\beta)(\gamma+\varepsilon_E)-\alpha\frac{K}{E}\varepsilon_K+\alpha\frac{\overline{ES}}{ES}\theta\mu+\alpha\frac{1}{ES}\left(\bar{\varepsilon}_Q-\varepsilon_Q\right)\right]$$

$$\frac{dK^{S2}}{dm}=\frac{dK}{de}\frac{de^{S2}}{dm}+\frac{dK}{dk}\frac{dk^{S2}}{dm}+\frac{dK}{dp}\frac{dp^{S2}}{dm}$$
$$=-\frac{1}{N}\frac{\alpha\beta Q}{EK}(\gamma+\varepsilon_E)-\frac{1}{N}\frac{\alpha(1-\alpha)Q}{E^2}\varepsilon_K+\frac{1}{N}\frac{\alpha\beta Q^2}{E^2K}\left(\theta\mu\overline{ES}+\bar{\varepsilon}_Q-\varepsilon_Q\right)$$
$$=\frac{1}{N}\frac{\alpha Q}{EK}\left[-\beta(\gamma+\varepsilon_E)-(1-\alpha)\frac{K}{E}\varepsilon_K+\beta\frac{\overline{ES}}{ES}\theta\mu+\beta\frac{1}{ES}\left(\bar{\varepsilon}_Q-\varepsilon_Q\right)\right]$$

$$\frac{dQ^{S2}}{dm}=\frac{dQ}{de}\frac{de^{S2}}{dm}+\frac{dQ}{dk}\frac{dk^{S2}}{dm}+\frac{dQ}{dp}\frac{dp^{S2}}{dm}$$
$$=-\frac{1}{N}\frac{Q^2\alpha\beta}{EK^2}(\gamma+\varepsilon_E)-\frac{1}{N}\frac{Q^2\alpha\beta}{E^2K}\varepsilon_K+\frac{1}{N}\frac{\alpha\beta Q^3}{E^2K^2}(\alpha+\beta)\left(\theta\mu\overline{ES}+\bar{\varepsilon}_Q-\varepsilon_Q\right)$$
$$=\frac{1}{N}\frac{Q^2\alpha\beta}{EK^2}\left[-(\gamma+\varepsilon_E)-\frac{K}{E}\varepsilon_K++\frac{\overline{ES}}{ES}(\alpha+\beta)\theta\mu+\frac{1}{ES}(\alpha+\beta)\left(\bar{\varepsilon}_Q-\varepsilon_Q\right)\right]$$

$$\frac{d\left(E/Q\right)}{dm}=\frac{\alpha}{e}\frac{dp^{S2}}{dm}-\frac{\alpha p}{e^2}\frac{de^{S2}}{dm}=\frac{\alpha}{e}\left[(\theta\mu\overline{ES}+\bar{\varepsilon}_Q-\varepsilon_Q)-\frac{p}{e}(\gamma+\varepsilon_E)\right]=\frac{1}{e}\left[\theta\mu\alpha\overline{ES}+(\bar{\varepsilon}_Q-\varepsilon_Q)\alpha-(\gamma+\varepsilon_E)ES\right]$$

Appendix E

Here we consider the effects of increased energy efficiency on energy use and energy intensity.

The production function is as follows:

$$Q = f(E, K, \alpha) = AE^{\alpha}K^{\beta}$$

From Appendix A we still have the following 1.o.c.:

$$\begin{aligned} pf'_E &= e \\ pf'_K &= k \end{aligned}$$

Total differentiating these with also allowing for changes in A gives:

$$\begin{aligned} pf''_{EE} \cdot dE + pf''_{EK} \cdot dK &= de - f'_E \cdot dp - pf''_{EA} \cdot dA \\ pf''_{KE} \cdot dE + pf''_{KK} \cdot dK &= dk - f'_K \cdot dp - pf''_{KA} \cdot dA \end{aligned},$$

where

$$\begin{aligned} f''_{EA} &= \alpha E^{\alpha-1}K^{\beta} > 0 \\ f''_{KA} &= \beta E^{\alpha}K^{\beta-1} > 0 \end{aligned}.$$

Setting $de = dk = dp = 0$, we find

$$\begin{aligned} \frac{dE}{dA} &= \frac{f''_{EK}f''_{KA} - f''_{EA}f''_{KK}}{N} > 0 \\ \frac{dK}{dA} &= \frac{f''_{EA}f''_{KE} - f''_{EE}f''_{KA}}{N} > 0 \end{aligned},$$

where N > 0, see Appendix A.

As both E and K increase, we also find that Q increases:

$$\frac{dQ}{dA} > 0$$

Consider now a change in α.

Total differentiating the first order conditions with respect to α gives:

$$pf''_{EE} \cdot dE + pf''_{EK} \cdot dK = de - f'_E \cdot dp - pf''_{E\alpha} \cdot d\alpha$$
$$pf''_{KE} \cdot dE + pf''_{KK} \cdot dK = dk - f'_K \cdot dp - pf''_{K\alpha} \cdot d\alpha$$

We find that

$$f''_{E\alpha} = \frac{(1+\alpha)}{E} f$$
$$f''_{K\alpha} = f'_K$$

Setting $de = dk = dp = 0$, we find

$$\frac{dE}{d\alpha} = \frac{1}{N}\left(-\frac{(1-\alpha)}{E} f \cdot f''_{KK} + f'_K \cdot f''_{EK} \right) > 0$$
$$\frac{dK}{d\alpha} = \frac{1}{N}\left(-f'_K \cdot f''_{EE} + \frac{(1-\alpha)}{E} f \cdot f''_{KE} \right) > 0$$

As both *E* and *K* increase when we have an increase in α, we get

$$\frac{dQ}{d\alpha} > 0 .$$

Appendix F

Here we explain how we have calibrated our model to the aluminum production in Norway.

The price of primary aluminum (p) in Europe has on average been around 2 euro/kg over the last eight years, i.e., around 2000 euro/ton.[27] The average price of electricity (e) in Norway (NO1; Southeast area) in 2015-24 was 54 euro/MWh (the average price in this decade was almost the same in all price areas in southern parts of Norway, i.e., NO1, NO2 and NO5, but slightly higher in NO2 since 2022).[28] The electricity intensity of aluminum ($ES = E/Q$) in Norway is around 13.5 MWh/ton.[29]

We use these numbers to calibrate α from the first order conditions in (3), i.e., $\frac{E}{Q} = \frac{p\alpha}{e}$:

$$\alpha = \frac{E}{Q}\frac{e}{p} = 13.5(\text{MWh/ton})\frac{2000\text{ (euro/ton)}}{54\text{ (euro/MWh)}} = 0.36$$

As a comparison, European Aluminum reports that the electricity cost share of primary aluminum is around 40%.[30] As electricity prices in Norway are somewhat lower on average than in other European countries (and the electricity intensity slightly lower), the share is likely somewhat lower in Norway.

In lack of good information, we assume the same cost share for capital, i.e., $\beta = 0.36$.

Production of primary aluminum (Q) in Norway in 2024 was 1.3 million tons.[31] This gives the following electricity use:

$$E = \frac{E}{Q}Q = 13.5(\text{MWh/ton})\cdot 1.3(\text{million tons}) = 17.6\text{ TWh}$$ CO_2 emissions (Scope 1)

from aluminum production in Norway in 2024 was 2.27 million tons.[32] Then we can compute the emissions factor of production (ε_Q):

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27 https://businessanalytiq.com/procurementanalytics/index/aluminium-price-index/
28 https://www.energy-charts.info/charts/price_average/chart.htm?l=en&c=NO
29 https://www.norskindustri.no/bransjer/aluminium/om-aluminiumsbransjen/
30 https://european-aluminium.eu/wp-content/uploads/2022/10/2022-05-20-european-aluminium-response-to-repowereu.pdf
31 https://investingnews.com/aluminum-production-by-country/
32 https://www.norskeutslipp.no/no/Komponenter/Klimakvoter/Kvoteutslipp/?ComponentType=kvoteutslipp&ComponentPageID=1103&SectorID=90

$$\varepsilon_Q = \frac{2.27 \text{ (million tons CO2)}}{1.3 \text{ (million tons)}} = 1.75 \text{ (ton CO2/ton aluminum)}$$

The price of emissions (m) in the EU ETS has been around 70 euro/tCO_2 over the last few years.

Norway's applied emissions factor (μ) has been set to 0.53 tCO_2/MWh (Norwegian Environment Agency, 2025). It was derived based on model simulations analyzing how one unit increase in the EU ETS price affects the Norwegian electricity price (i.e., (euro/MWh)/(euro/tCO2), gives the same unit as above - tCO_2/MWh). In other words, we have $\gamma = \mu = 0.53$ tCO_2/MWh. Note, however, that the Norwegian electricity market is divided into five bidding zones, with very different electricity prices over the last few years. Thus, we consider also different values of γ in our simulations.

The support share (θ) in Norway is set to 0.75, which is the maximally allowed share.

The aluminum firms in Norway received 2.15 million EU ETS allowances in 2024, implying an average share of free allocation to aluminum firms in Norway of 95% (see below).[33] This gives the following number of free allocations per ton of aluminum produced ($\bar{\varepsilon}_Q$):

$$\bar{\varepsilon}_Q = 0.95 \cdot 1.75 \text{ (ton CO2/ton aluminum)} = 1.65 \text{ (ton CO2/ton aluminum)}$$

Finally, the electricity consumption efficiency benchmark ($\overline{ES}$) for primary aluminum was 13.9 in 2021, which implies $\overline{ES} = 13.45$ in 2024 (it is reduced by 1.09% per year).[34]

Table F1 (which is the same as Table 1 in the main text) summarizes the parameter values derived from the calibration.

Table F.1 Calibrated parameter values for Norwegian aluminum production

Parameter	Value	Unit
p	2000	euro / ton aluminum
e	54	euro / MWh

33 https://www.norskeutslipp.no/no/Komponenter/Klimakvoter/Kvoteutslipp/?ComponentType=kvoteutslipp&ComponentPageID=1103&SectorID=90

34 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=oj:JOC_2021_528_R

α	0.36	
β	0.36	
μ	0.53	tCO_2/MWh
γ	0.53	tCO_2/MWh
θ	0.75	
ε_Q	1.75	ton CO_2 / ton aluminum
$\bar{\varepsilon}_Q$	1.65	ton CO_2 / ton aluminum
ES	13.5	MWh / ton aluminum
$\overline{ES}$	13.45	MWh / ton aluminum