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Benchmarks for emissions trading – general principles for emissions scope

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Abstract

Greenhouse gas emission benchmarks are widely implemented as a policy tool, as more countries move to implement carbon pricing mechanisms for industrial emissions. In particular, benchmarks are used to determine the level of free allowance allocation in emission trading schemes, which are distributed as a measure to prevent carbon leakage. This paper analyses how benchmark designs impact firms' production and business model decisions, particularly focusing on the coverage of direct and indirect emissions in the benchmark scope. We develop an analytical model and use the example of a steel mill to analyze and quantify how scope of indirect emissions coverage affect incentives. We seek to clarify generalized principles for efficient benchmark design, that provide a predictable policy framework for innovation and investment to decarbonize energy intensive industry.

Keywords: Emissions Trading; Emission Benchmarking; Free allocation; Incentives; Low-Carbon Innovation.
JEL Classification: D04, H25, L51, L61, Q58

1. Introduction

Emissions from industry account for a third of total global greenhouse gas emissions (IPCC, 2014). These emissions will need to be reduced significantly in order to meet long-term climate change mitigation goals. To deliver industrial emissions reductions, introducing a carbon price through an Emission Trading System (ETS) is the preferred policy tool in many regions. However, a key challenge facing ETS implementation is the need to address carbon leakage risk for energy intensive activities. These activities bear large incremental costs from carbon pricing, and there is

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concern that if large carbon price differences persist internationally, these sectors may relocate production and pollution towards regions with low carbon prices rather than reducing overall emissions, thus undermining the environmental effectiveness of emissions trading.

To avoid these risks, the default method adopted in emissions trading is to grant free emission allowances to vulnerable sectors (e.g. in EU, California, China, Korea, and New Zealand) (see Appendix A for a summary of international ETSs). The idea is to compensate firms for carbon prices differentials to level the playing field with regions without equivalent carbon pricing. Yet free allocation can introduce a number of problems to the system, not least by undermining incentives to cut emissions. The linkages between alternative free allocation rules and their impact on efficiency and distributional outcomes are increasingly understood and adopted into ETS design. For example, it is well documented that granting free allocation based on a historic emission baseline (*ex-ante* allocation), as was done during the two initial phases (2005-2012) of the EU ETS, can create early action problems and other economic distortions, and over compensate polluters resulting in large windfall profits (Sterner and Muller, 2008; Neuhoff et al., 2006; Sijm et al., 2006; Chen et al., 2008). In response to the issue of over-allocation, there has been a move towards Output Based Allocation (OBA, also called *ex-post* or dynamic allocation), that is, linking free allocation volumes to more directly to current or recent output levels, making the free allocation marginal, rather than inframarginal. To incentivize efficiency and early action, benchmarking was introduced in the EU ETS Phase three (2013-2020) and this has been widely replicated in other systems.

In general, emissions benchmarking is a tool to compare the emissions intensity of production between facilities or firms. A product benchmark may be set to reflect a “best in class” or a “best available technology” emissions performance. If free allocation is distributed in proportion to output multiplied by the product benchmark, the facility has an incentive to meet or even beat the benchmark level. Benchmarking is an attractive policy tool from an economic point of view because it provides incentives for emission abatement without prescribing a certain technology. As it is often unknown which technologies will prove most successful at cutting emissions cost-effectively, benchmarking facilitates competition by leaving the innovation space open to all technologies.

The increasing use of benchmarks raises the need to better understand and ensure their efficacy. The design of benchmarks needs to consider that production processes are typically complex involving multiple inputs and outputs. Thus, it is not surprising that benchmarking design is largely driven by technical and engineering perspective, often ignoring economic incentives. However, economic analyses show that applying benchmarking to free allocation indeed affects abatement incentives (Zetterberg, 2014) and that specific benchmark designs can give rise to perverse incentives with respect to trade and input use (Branger and Sato, 2017). Behaviourally, firms tend to treat benchmarks as a focal point for emissions efficiency improvements under OBA, more so than under *ex-ante* allocation) (Branger and Sato, 2017) thus the importance of designing more precise and efficient benchmarks is magnified under output based allocation. Ignoring distortions from benchmarks is problematic because ultimately, it undermines the incentives for efficient operation and investments, which are required to deliver technological progress and deep emission cuts in these sectors.

This paper revisits emission benchmarks design, focusing on how to take account of input factors and by-products, and their associated emissions in the design of benchmarks. We develop an analytical model and use the example of a steel mill to analyze how the coverage of indirect emissions in the benchmark scope affects firms’ mitigation and production decisions. Indirect emissions represent those attributed to purchased energy or input materials that are sourced from off-site facilities, and indirect emissions savings are attributable to by-products such as heat, which replace carbon intensive inputs into production processes, either on-site or off-site.

We propose a systematic scope adjustment to make benchmarked allocation business-neutral i.e. independent of plant configuration. In doing so, we extend the current concept of benchmarks to reflect up- and down-stream processes. We then use steel plant data to quantify the impact of scope adjustment on volumes of allowance allocation. We furthermore explore whether complementing benchmarking with a consumption charge on the carbon content of basic materials as suggested in the literature (Böhringer et al., 2017; Neuhoff et al., 2014), can fully restore optimal abatement incentives along the value chain. Some fundamental benchmark principles emerge from this analysis. Overall, the results demonstrate the importance of going beyond technical benchmarks and adopting well-defined system boundaries in benchmark design to drive efficient input and output choice.

The paper is structured as follows. Section 2 gives an overview of the key elements of emission benchmark design and the economic incentives they impact. In Section 3, the concept of the new benchmark framework is laid out, including a description of the basic analytical model. Section 4 uses the analytical model and four examples in a steel plant context to analyze how adjusting benchmark scope affects production incentives. In Section 5, we quantify the magnitude of the corrected distortions using steel plant data. Section 6 assesses how to retain carbon price incentives along the whole value chain, by combining benchmarks with a downstream consumption charge. The paper ends with a conclusion.

2. Elements of emission benchmark design

Plants producing the same good can differ in numerous ways, for example in terms of (i) technology choice including resource recovery and reuse, (ii) inputs composition, including the fuel choice and options to produce on-site or purchase intermediate inputs, and (iii) output composition (by-products, waste products). How can product benchmarks then be designed to make a business-neutral and fair comparison of plant level emissions, and provide consistent incentives for abatement and efficient technology choice? This section discusses some of the key considerations of benchmark design, highlighting the dimensions that can create incentive distortions.

In terms of what should be benchmarked, the most commonly used type of emissions benchmarking is a product specific benchmark that is expressed as emissions per unit of output. In principle, product benchmarking is relatively straightforward to develop for sectors producing homogeneous products, while it can be more complicated for sectors with heterogeneous products given emissions data is required at the level of the individual product. Product benchmarks reward emissions efficiency in the production process e.g. through a switch to clean fuels, and avoids discriminating by technology, fuel mix, size or age of plant, or other specific circumstances such as raw material quality. When product benchmarks are more difficult to define, for example for multi-product sectors such as the chemicals sector, heat-carrier, or fuel then benchmarks can be applied as a fall-back option. In the EU ETS, these fall-back fuel benchmarks are based on natural gas as reference fuel.[1]

There is considerable heterogeneity across emissions trading schemes in the selection of which stage of the value chain the benchmark is placed. (see Appendix A). In theory, a benchmark can be applied at any stage of the value chain without affecting incentives, as long as upstream and downstream emissions are appropriately taken into account, as this paper will show. In practice, a number of factors come into play: transaction costs for benchmarking increase as one moves down the value chain because the cost of obtaining data increases with the level of product differentiation; most emissions tend to be focused in the upstream basic products, such that the small benefit in terms of carbon emissions covered, from moving down the value chain, may not be justified compared to the additional transaction costs of covering more products; a sufficient number of

[1] An alternative approach would be to use the average fuel mix of the industry in order to obtain more realistic benchmarks.

facilities producing each product to ensure the benchmarks are representative enough and, thus, perceived as fair.[2] This suggests benchmarking should target upstream, homogeneous products.

Benchmarks can be based on integrated plants or stand-alone plants. Industrial production in an integrated plant is typically more CO_2 efficient than in stand-alone plants because of opportunities to recover and reuse energy including heat, and waste gases (U.S. Environmental Protection Agency, 2009). For example, coke is a key, carbon intensive input into steel production. Coke production results from carbonizing coking coal in airtight coke ovens, and is accompanied by a number of by-products including coke oven gas, which can be reused in integrated plants. A product benchmark based on an integrated production process would then reflect the most efficient technology, and support the use and reuse of heat, waste gases, and other energy recovery whenever efficient from a global perspective. Currently the EU ETS divides production units into sub-installations rather than setting product benchmarks based on integrated processes (European Commission, 2011).

In terms of updating benchmark values over time, while updating is necessary to keep benchmarks ambitious and reflect the improvements in technology, updating can also create early action problems, by linking mitigation actions today with allocation in the next period (Böhringer and Lange, 2005; Rosendahl, 2008). This is particularly problematic for incentivizing investment in radical or "break-through" innovations like carbon capture and storage (CCS), as implementing such technologies could reduce future free allowances sharply. Anticipating this, firms may collude against adopting such innovations. A case may be made then be made to refrain from updating benchmark values in some instances, such that early adoptors of radical technologies can recover part of the innovation costs through the stream of income from continued free allocation. Practically, this may be implemented in a number of ways. First, is to expand the pool of installations from which the benchmark is derived; for example by harmonizing and coordinating benchmarks with other regions' ETS. Changes in the emission intensity of one plant would then only have a very small effect on the benchmark calculation (Zetterberg, 2014; Rosendahl and Storrøsten, 2015). Second, a 'diffusion-threshold' could be applied, whereby a benchmark is updated to reflect a radical technological leap only if it becomes adopted by a sizable share of the plants. A third option is to guarantee that the BM updating will reflect incremental efficiency improvements only, and break-through technologies will not be taken into account.

Finally on scope of emissions coverage, total emissions of a production unit include both direct and indirect emissions. For example, a blast furnace plant can produce coke on-site releasing direct emissions or it can source it from a stand-alone coking plant, thus producing indirect emissions. On the output side, plant emissions are typically attributed to its main product, yet all industrial processes also give rise to by-products (Kronenberg and Winkler, 2009)[3], some of which can create indirect emissions savings. For example, electricity and heat is often a by-product of industrial plants and can be reused on-site or sold to other production processes or district heating (see Figure 1). Indirect emissions and savings are typically excluded from the scope of product benchmarks such that firms are incentivized to only focus on reducing the direct emissions to maximize free allocation. There are a number of exceptions that demonstrate that benchmark scope can include indirect emissions, for instance from purchased electricity, to level the playing field between plants of different configurations[4]. For example, in the EU ETS *"In order to ensure that benchmarks lead to reductions in greenhouse gas emissions, for some production processes in which direct emissions eligible for the*

[2] The representativeness of a benchmark might also be at risk when there are only a small number of plants using a certain technology.

[3] Kronenberg and Winkler (2009) argue, using an evolutionary perspective on production, that economies adapt to find useful purposes for joint outputs.

[4] See Appendix A.

free allocation of emission allowances and indirect emissions from electricity production not eligible for free allocation on the basis of Directive 2003/87/EC are to a certain extent interchangeable, the total emissions including indirect emissions related to the production of electricity have been considered for the determination of the benchmark values to ensure a level playing field for fuel and electro-intensive installations." (European Commission (2011), para (7)). In the next Section, we explore how benchmark scope affects the economic incentives of firms.

3. A new framework for emission benchmarks - Scope adjusted benchmarks

We propose a framework for emission benchmarks that allows for a systematic adjustment of emissions scope, to ensures a business-neutral approach to the allocation of free allowances. This is illustrated using the example of an integrated steel plant production process.

3.1. Direct and indirect emissions of an integrated plant - a steel example

The primary steel production process is typically based on ironmaking in an integrated blast furnace (BF) where the iron in the sinter and pellets, is reduced to hot metal (pig iron) using coke as a reducing agent and energy source. As shown in Figure 1, direct emissions comes from all on-site facilities. An integrated BF plant typically has its own electricity generation, coking and sintering plants. Traditionally, the benchmark scope accounts for direct emissions only, and attribute it all to the main product output.

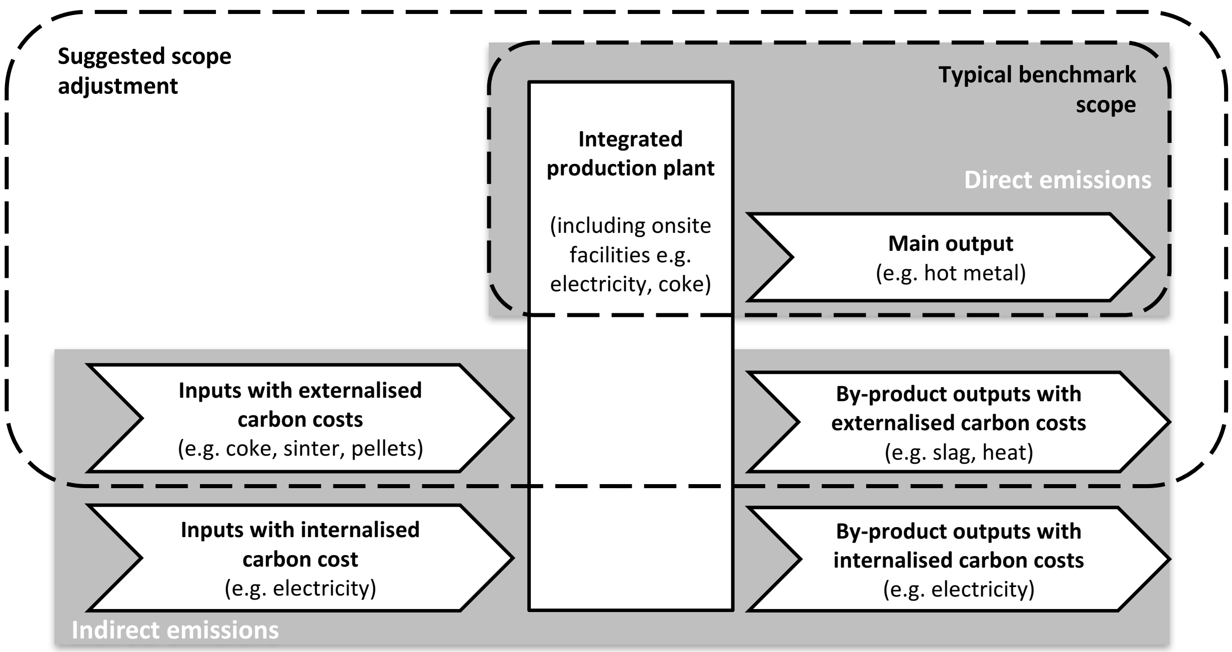

Figure 1: Simplified illustration of the direct and indirect emissions from an integrated production facilities using an example integrated blast furnace plant in steel making. Source: Authors

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As illustrated in Figure 1, integrated plants also have indirect emissions, for example if it purchases additional coke, sinter or electricity from off-site facilities. Pellets are usually purchased from off-site plants(Siitonen et al., 2010). On the output side, in addition to the main output, the BF process creates a number of by-products, the important ones being slag, heat, blast furnace gas and electricity. The heat and BF gas can be recovered and reused on-site or off-site, either directly or as an input for electricity generation. Slag can be processed into granulated slag and used as a low-carbon substitute for clinker in cement production.

Yet, indirect emissions and savings are typically excluded from the scope of product benchmarks. Thus firms are incentivized to focus only on reducing the direct emissions to maximize free allocation, rather than considering options to minimize overall emissions throughout the value chain.[5] We show that the scope of emissions coverage in benchmarks can influence the decisions of an integrated plant, and that systematic adjustment of benchmark emissions scope can help realign incentives.

Which indirect emissions should be adjusted for in the benchmark scope? Figure 1 shows inputs and outputs can be distinguished by carbon cost incidence i.e. those where the carbon costs are internalized or externalized. For example with electricity inputs under the EU ETS, carbon prices are internalized in the prices of electricity, because allowances are fully auctioned and there is full cost pass through. In contrast with other inputs such as coke, carbon prices are externalized, because coke plants receive free allocation based on OBA, such that there is limited cost pass through - even if a firm is less efficient than the benchmark, under international competition, only the carbon costs exceeding the benchmark level is marginal and thus passed through. On the output side, what matters is whether carbon prices are internalized or externalized in the prices of the competing product that the by-product displaces. With slag, carbon prices are externalized in the price of the competing product clinker, because like coke, clinker production receives free allocation under OBA. The electricity output instead competes with grid electricity for which carbon costs are internalized in the product price.

3.2. Proposal for benchmark scope adjustment

The proposed benchmark scope adjustment takes account the indirect emissions from inputs and outputs, where carbon costs are not internalized. Under this framework, free allocation to firm i, a_i, is defined as follows:

$$a_i = q_{p_i} BM_p - q_{m_i} BM_m + q_{b_i} BM_b \tag{1}$$

where BM_p is the product benchmark for q_p, which is the output quantity of the main product. The free allocation is then scope adjusted in two ways. A reduction is made through the term $q_m BM_m$ for out-sourcing inputs (e.g. sinter, pellets, coke) and a bonus is given by $q_b BM_b$ for the production of by-products that generate emissions savings (e.g. slag, heat).[6]

To assess the incentive effects of product benchmarks, we employ a simple profit maximization problem of firm i, which can be described by the following equation:

$$Max \quad \Pi_i = p_q q_i + p_B B_i - p_I I_i - c_i(I,O) - p_e e_i(I,O) + p_e a_i \tag{3}$$

[5] From an overall steel sector perspective, emissions abatement is expected to come from a number of channels including the reduction of fuel use, reduction of material inputs, reduction of yield losses (Milford and Cullen, 2011), improvement of energy recovery, improved material byproduct recovery (ESTEP and EUROFER, 2014), increased share of steel produced through recycling (Pauliuk and Allwood, 2013) and CCS.

[6] We adopt a framework where the scope adjustment is modelled in the allocation formula. One could however also imagine a model framework where the adjustment is made directly in the benchmark formula. The equivalent to equation 1 in terms of a scope adjusted benchmark would then be:

$$a_i = q_{p_i} SABM_{p_i} \quad where \quad SABM_{p_i} = BM_p - \frac{q_{m_i}}{q_{p_i}} BM_m + \frac{q_{b_i}}{q_{p_i}} BM_b \tag{2}$$

The underlying assumption here is that the main product benchmark, BM_p, is based on the most CO_2 efficient production process. This assures that plants do not receive an over-allocation of free allocation because of off-site inputs.

where q_i is the quantity produced of benchmarked product by firm i with price p_q, which depends on the overall demand for the product $(\sum_{j=1}^{n} q_j)$[7], B_i are other outputs or by-products of the firm, with corresponding prices p_B, I_i are inputs of the firm with prices p_I, c_i is the cost function of the firm, which depends on all inputs and outputs, e_i is the emission function of firm i, which depends, again, on all inputs and outputs and for which the allowance price p_e has to be paid, and a_i is the free allocation the firm receives. This paper considers a firm to be a production site. However, this analysis can be transferred to any level of business activity e.g. plant, installation, or firm.

Our analytical model relies on a few key assumptions. First, we assume output based allocation, hence allocation is aligned with recent or actual output. Benchmarks are increasingly applied in the context of OBA, including in California and the EU ETS Phase 4 (post 2020).[8] Moreover, as we are concerned about factors influencing decisions about the production process, assuming a production based allocation is more suitable than a capacity based one. Second, we focus on product benchmarks, which are the most widely used type of benchmarks in current emission trading schemes (see Appendix A). Third, we assume full carbon cost pass through in electricity prices. This assumption is generally supported by empirical studies in the EU ETS (Fabra and Reguant (2014); see Arlinghaus (2015) for an overview). Fourth, we assume zero cost pass through in all sectors other than electricity. Given the first assumption above, this approximates the effect of output based allocation with cost pass through limited to the carbon cost difference between the plant's emission intensity and the benchmark.

4. Economic incentives under scope adjusted benchmarks - examples in steel production

For each of the four categories of indirect emissions identified in Section 3.1, we now test how adjusting the emissions scope coverage changes incentives compared to more traditional benchmark designs. We employ the standard profit maximization problem from equation 3 and assess how the scope adjustment can level the playing field between plants with different plant configurations. To evaluate whether a scope adjustment is appropriate or not, we introduce an additional parameter, γ, which determines the scope adjustment of the benchmark which takes the value 0 for no adjustment and 1 for full adjustment.

4.1. Case 1: Inputs with non-internalized carbon costs

First, we examine the case of indirect emissions attributed to inputs for which carbon prices are not reflected in the price. This can be exemplified by a blast furnace plant with an on-site coking plant, which has an option to substitute between coke produced on- and off-site. The main product is hot metal (for simplicity we call it steel).

The profit function of the steel plant is defined as follows:

$$\begin{aligned} Max \quad \Pi_{s_i} = p_s q_{s_i} - p_k k_{off_i} - c_{s_i}(I, O, k_{tot}) - c_{k_i}(I, O, k_{on}) - p_e e_{s_i}(I, O, k_{tot}) \\ -p_e e_{k_i}(I, O, k_{on}) + p_e a_i \end{aligned} \tag{4}$$

[7]Results of our analysis also hold for other market structures, e.g. perfect competition.

[8]OBA has a number of advantages over *ex-ante* allocation. It has been shown that carbon leakage is prevented more effectively with OBA (Demailly and Quirion, 2006; Fischer and Fox, 2012; Meunier et al., 2014). OBA also avoids politically contentious surplus allocation and associated windfall profits as well as threshold effects (Branger et al., 2015; Quirion, 2009). An issue with OBA is that limited carbon cost pass through is expected, thus emission reduction incentives in the value chain are largely foregone (Munnings et al., 2016). This is further discussed in Section 6.

Here, the cost and emission functions are split into that of steel making and the on-site coke-making. The cost function is thus defined as the sum of the two process' costs: $c(I, O) = c_s(I, O, k_{tot}) + c_k(I, O, k_{on})$. The cost function of the steel making process, *inter alia* depends on the total amount of coke used, k_{tot}. The cost function of the coking process depends on the share of on-site coke, $(1-\alpha)k_{tot}$, used in hot metal making, where α is defined as the share of off-site coke with respect to the total amount of coke used, $\alpha = \frac{k_{off}}{k_{tot}}$. The more coke is produced on-site, the higher the costs of the on-site coking process. We assume that all the coke produced on-site is consumed on-site. The price of purchased coke does not reflect carbon prices, because of output based allocation. We assume a competitive market for coke.

The benchmark scope is extended to account for indirect emissions attributable to off-site coke production, by adjusting the free allocation according to Equation 1 (abstracting from the output side in this case):

$$a_i = q_{s_i} BM_s - \gamma \alpha k_{tot_i} BM_k \tag{5}$$

where q_{si} is the current output of steel. The steel benchmark, BM_s, assumes all coke is produced on-site.[9] The free allocation is thus reduced according to the share of off-site coke used in production. The scope adjustment parameter γ is used to assess whether and at what scale a scope adjustment is required.

We are interested in firms' choice of α, with and without the adjustment.[10] Substituting for k_{on_i} with $(1-\alpha)k_{tot_i}$ and replacing k_{off_i} with αk_{tot_i} in the profit maximization problem (equation 4), differentiating with respect to the share α of off-site coke, and using the optimizing condition $\frac{\partial \pi_i}{\partial \alpha} = 0$ determines the equilibrium choice of the share of off-site coke:

$$p_k + p_e \gamma BM_k = \frac{\partial c_k}{\partial k_{on}} + p_e \frac{\partial e_k}{\partial k_{on}} \tag{6}$$

Firms will choose a share of on-site coke at which the marginal costs of producing coke on-site, $\frac{\partial c_k}{\partial k_{on_i}} + p_e \frac{\partial e_k}{\partial k_{on_i}}$, equals the sum of costs of buying coke off-site and the reduction of free allowance allocation, $p_k + p_e \gamma BM_k$.

As long as off-site coke prices, without internalized carbon costs, are competing with on-site coke costs, which incorporate carbon costs, a full scope adjustment of the benchmark is needed in order to provide a level playing field for coke inputs. Marginal costs of on-site and off-site coke should therefore be equal. As can be calculated from equation 6, under the condition that the on-site emission intensity equals the benchmark emission intensity, the adjustment parameter thus equals one ($\gamma = 1$). The scope adjustment neutralizes incentives of displacing direct emissions with indirect emissions by internalizing the carbon cost of inputs, thus realigning incentives for efficient choice of inputs. When there is full scope adjustment, i.e. $\gamma = 1$, the proposed scope adjustment is optimal in the sense that it re-installs a situation where carbon costs of inputs are fully internalized. [11]

[9] Whether inputs are assumed to be produced on-site or off-site depend on the typical configuration of a plant. Either way, correct scope adjustments can neutralize the disincentives for less emissions efficient choices.

[10] We do not rule out corner solutions but assume long term cost functions that allow for investment costs hence capacity expansion, and focus here on the internal solutions where $k_{on} > 0$ and $k_{off} > 0$. This means that even if initially $k_{off} = 0$, the same adjustment is appropriate as policy can induce investment into on-site coke production over a sufficiently long term horizon.

[11] Comparing the input choice of off-site coke (equation 6) with the input decision a firm faces when carbon costs are internalized in the price of the off-site input and no free allocation is given:

$$Max \quad \Pi_{s_i} = p_s q_{s_i} - p'_k k_{off_i} - c_{s_i}(I, O, k_{tot}) - c_{k_i}(I, O, k_{on}) - p_e e_{s_i}(I, O, k_{tot}) - p_e e_{k_i}(I, O, k_{on}) \tag{7}$$

The adjustment for inputs examined here allows making fair comparisons between plants of different configurations, with varying shares of inputs produced on-site or off-site. It is however applicable for any carbon intensive input for which the price does not internalize carbon costs, not only for coke inputs. For example, adjustment may be made for sinter and pellets in the case of steel, or for off-site clinker in the case of a cement benchmark, or for pulp in the case of a paper benchmark.

4.2. Case 2: Inputs with internalized carbon costs

We now assess the case of an input where the carbon cost is internalized in the input price, using electricity input in steel as an example. We assume that the price of the purchased electricity from the grid fully reflects the marginal cost of carbon in electricity generation. The profit function of a steel plant that buys electricity from the grid is:

$$Max \quad \Pi_{s_i} = p_s q_{s_i} - (p_{el} + p_e EI_{el}) Q_{el_i} - c_{s_i}(I,O) - p_e e_{s_i}(I,O) + p_e a_i \tag{8}$$

where EI_{el} is the emission intensity of the production process of electricity and with free allocation being scope adjusted and thus based on the steel output and the share of off-site electricity bought, $a_i = q_{s_i} BM_s - \gamma \alpha q_{el_i} BM_{el}$, with $\alpha = 1$.

Instead, a steel plant that generates all electricity on-site has the following profit function:

$$Max \quad \Pi_{s_k} = p_s q_{s_k} - c_{el_k}(I,O) - c_{s_k}(I,O) - p_e e_{s_k}(I,O) - p_e e_{el_k}(I,O) + p_e a_k \tag{9}$$

with free allocation being based on the steel output and the share of off-site electricity. As we assume that all electricity is generated on-site, $\alpha = 0$, and thus free allocation boils down to $a_k = q_{s_k} BM_s$.

We use the optimizing condition that the first order conditions of the two plants are set equal to zero ($\frac{\partial \Pi_{s_i}}{\partial q_{el}} = 0$, $\frac{\partial \Pi_{s_k}}{\partial q_{el}} = 0$) and assume that electricity has the same marginal product for both plants ($\frac{\partial q_{s_i}}{\partial q_{el}} = \frac{\partial q_{s_k}}{\partial q_{el}}$) to compare the relation of the cost structures of the two plants.[12] Assuming the same emission intensity in the purchased and in the produced electricity, $EI_{el} = \frac{\partial e_{el}}{\partial q_{el}}$, and assuming that the price of off-site electricity equals the marginal costs of producing electricity on-site, $p_{el} = \frac{\partial c_{el}}{\partial q_{el}}$, reveals the following relation of the costs incurred by the two firms:

$$\frac{\partial c_{el}}{\partial q_{el}} + p_e \frac{\partial e_{el}}{\partial q_{el}} + \frac{\partial c_{s_i}}{\partial q_{el}} + p_e \frac{\partial e_{s_i}}{\partial q_{el}} + p_e \gamma BM_{el} = \frac{\partial c_{el_k}}{\partial q_{el}} + p_e \frac{\partial e_{el_k}}{\partial q_{el}} + \frac{\partial c_{s_k}}{\partial q_{el}} + p_e \frac{\partial e_{s_k}}{\partial q_{el}} \tag{10}$$

The left hand side reflects the costs for the plant buying electricity from the grid, and the right hand side reflects the costs for a plant producing electricity on-site. As can be calculated from equation 10, this equality only holds when the adjustment parameter is zero, $\gamma = 0$, assuming that the emission intensity of on-site production equals the benchmark emission intensity.

A scope adjustment on the other hand, $\gamma \neq 0$, would lead to an increase in the electricity costs for the firm buying electricity off-site by $p_e \gamma BM_{el}$. Such an adjustment would thus uneven the level playing field across firms purchasing the input versus firms producing the input on-site. In the

where the price of the off-site coke now includes carbon costs, $p'_k = p_k + p_e EI_k$, where EI_k represents the emission intensity of the coke production process per ton of coke. If the coke plant produced at the benchmark level, the emission intensity would equal the coke benchmark, $EI_k = BM_k$. Rearranging the first order condition of the profit function (equation 7), differentiated with respect to the share of off-site coke, and assuming that the firm produced at the benchmark level, $EI_k = BM_k$, yields the same as equation 6.

[12] The marginal costs of buying electricity off-site for plant i are $MC_i = p_{el} + p_e EI_{el} + \frac{\partial c_{s_i}}{\partial q_{el}} + p_e \frac{\partial e_{s_i}}{\partial q_{el}} + p_e \gamma BM_{el}$ and of producing electricity on-site for plant k are $MC_k = \frac{\partial c_{el_k}}{\partial q_{el}} + p_e \frac{\partial e_{el_k}}{\partial q_{el}} + \frac{\partial c_{s_k}}{\partial q_{el}} + p_e \frac{\partial e_{s_k}}{\partial q_{el}}$

case of inputs with internalized carbon costs, firms might thus end up paying twice for the carbon externality. This evaluation holds for any other input with internalized carbon costs. However, in practice, there are only very few inputs which have carbon costs internalized already.

4.3. Case 3: Outputs competing with goods with non-internalized carbon costs

Next we examine whether scope adjustment should be made for by-products that generate indirect emissions savings in other production processes. A major by-product of primary steel making is slag. Slag is a low-carbon substitute for clinker, which is a carbon intensive basic input factor to cement making (Benhelal et al., 2013). By displacing (or providing an equivalent service to) clinker, slag production generates indirect emissions savings and reduces overall emissions, thereby enhancing social welfare. However, for the blast furnace plant, producing extra slag can increase marginal emissions and, hence, the marginal costs of steel (Buttiens et al., 2016).

Slag competes directly with clinker producers. Clinker production volumes dominate the market and thus we assume it to be price setting for clinker (and hence also slag).[13]. The clinker producer faces the following profit optimization problem:

$$Max \quad \Pi_{cl_i} = p_{cl}q_{cl_i} - c_{cl_i}(I,O) - p_e e_{cl_i}(I,O) + p_e a_{cl_i} \tag{11}$$

Clinker producers receive free allocation according to the clinker benchmark:

$$a_{cl_i} = q_{cl_i} BM_{cl} \tag{12}$$

From the first order condition, it follows that the clinker producer will sell clinker at the following price, assuming that they do not pass through carbon prices due to output based allocation:

$$p_{cl} = \frac{\partial c_{cl_i}}{\partial q_{cl_i}} + p_e \frac{\partial e_{cl_i}}{\partial q_{cl_i}} + p_e BM_{cl} \tag{13}$$

The steel plant's profit function, including the slag output (q_{sl}) is:

$$Max \quad \Pi_{s_i} = q_{s_i}p_s + p_{sl}q_{sl_i} - p_I I_i - c_{s_i}(I,O) - p_e e_{s_i}(I,O) + p_e a_{s_i} \tag{14}$$

The benchmark scope is extended to account for indirect emission savings attributable to slag displacing clinker production, by adjusting free allocation to the blast furnace plant according to Equation 1(abstracting from the input side in this case):

$$a_{s_i} = q_{s_i} BM_s + \gamma\beta q_{sl_i} BM_{cl} \tag{15}$$

where γ is the scope adjustment parameter, β is a conversion factor for the quantity of slag needed to substitute one metric ton of clinker in cement production[14], and BM_{cl} is the benchmark for

[13] In this example, we ignore market structures that might lead to temporary higher or lower revenues from e.g. slag sales dependent on product quality, location, and time. Steel producers often claim that the slag market is a "buyers market" in reality, meaning that the steel producers face a monopoly situation when selling to the cement producer who is essentially setting the price for slag. Such a monopolistic situation might imply that clinker and slag prices are not fully comparable nor interchangeable. We also assume that all slag produced is released to the market and sold for use in cement.

[14] For simplicity, we assume a linear relationship. Note however that a full, meaning 100%, substitution of clinker by slag is not possible.

clinker. Here, slag receives an adjustment according to the clinker benchmark, rather than creating an additional slag benchmark, because it saves emissions in proportion to the clinker it displaces.[15]

Setting the first order condition equal to zero for the optimality condition, the steel producer will provide slag until marginal product equals marginal costs:

$$p_{sl} = \frac{\partial c_{s_i}}{\partial q_{sl_i}} + p_e \frac{\partial e_{s_i}}{\partial q_{sl_i}} - p_e \gamma \beta BM_{cl} \tag{16}$$

In an efficient economic market, prices and thus costs of clinker will equal the service equivalent of slag (comparing equation 13 and equation 16):

$$\frac{\partial c_{cl_i}}{\partial q_{cl_i}} + p_e \frac{\partial e_{cl_i}}{\partial q_{cl_i}} + p_e BM_{cl} = \frac{\partial c_{s_i}}{\partial q_{sl_i}} + p_e \frac{\partial e_{s_i}}{\partial q_{sl_i}} - p_e \gamma \beta BM_{cl} \tag{17}$$

This equation however only holds if $\gamma = 1$, implying the need for full scope adjustment. The scope adjustment for the indirect emissions savings of slag production ($-p_e \gamma \beta BM_{cl}$) thus reduces marginal cost of slag to make it competitive with clinker, which receives free allocation. This adjustment encourages the cement company to substitute more clinker with low-carbon slag, thus reducing overall emissions (See Appendix B on the cement plant's decision on slag and clinker).

Figure 2 illustrates the level of free allocation per metric ton of hot metal depending on the slag production. With an unadjusted benchmark (dotted line), free allocation stays constant, independent of slag output. Instead with scope adjustment, free allocation is increased according to slag output. The baseline hot metal benchmark is lower in the scope adjusted benchmark case, as the unadjusted benchmark assumes some amount of slag production.

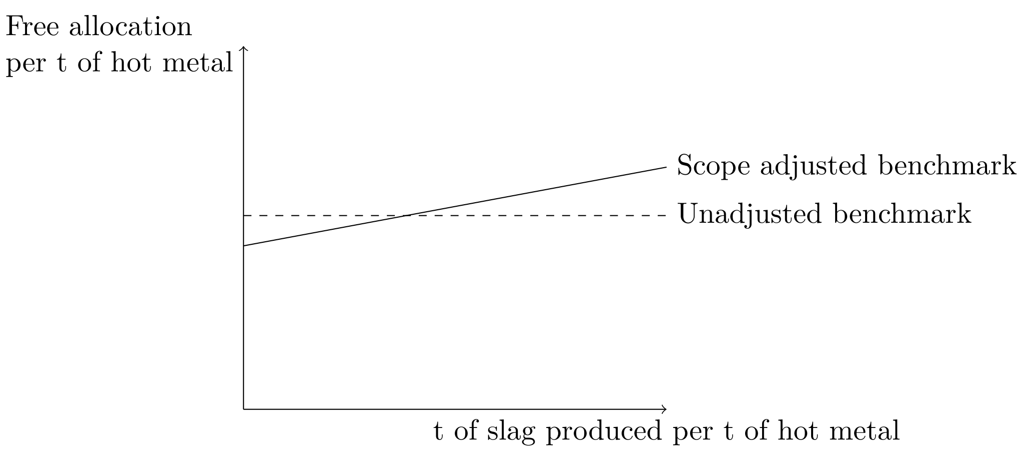

Figure 2: Free allocation per metric ton of hot metal with unadjusted benchmark, dashed line, and with scope adjusted benchmark, solid line. In the case of the unadjusted benchmark, no emissions are attributed to the by-product and thus the hot metal benchmark is independent of the amount of slag produced.

Allocating free emissions to by-products does not necessarily lead a higher total allocation. Existing ETS benchmarks attributes total emissions to the main product and does not explicitly

[15]The adjustment for the amount of slag only applies to slag which is sold in the market, not stored. Slag use needs to be feasible, e.g. artificial constraints on building codes that inhibit substitution need to be addressed. Policy support to induce demand for slag may be necessary, such as public procurement of low carbon steel or eco-building standards. Otherwise the economic incentive cannot work and might have perverse results.

[15]We focus on interior solutions here. There is always some slag co-production such that q_{sl} is greater than 0. As before, cost functions are long term and the same adjustment is appropriate for additional slag capacity.

attribute emissions to by-products, however, it implicitly assumes that some level of by-products is produced. If emissions are explicitly attributed for by-products with scope adjustment, a recalculation of the main product benchmark is necessary for every such by-product.

The scope adjustment studied here is also applicable to any industrial by-products that compete with goods receiving free allocations. For example, heat represent by-products in the steel production process and if captured, can be sold for district heating, providing the equivalent service to conventional heat generation through gas or electricity. In the EU ETS, free allocation is given to heat plants on the ground of distributional concerns, such that carbon costs are not passed through to heat prices. To incentivize industrial plants to optimize heat recovery, reuse and supply, scope adjustment is necessary so that their by-product heat can compete with other heat producers.

4.4. Case 4: Outputs competing with goods with internalized carbon costs

By-products with indirect emissions savings may also face competition from goods, where carbon costs are internalized in the prices already. We use the example of electricity produced as a by-product in a steel plant, which can displace fossil generated electricity (from the grid) thus creating indirect emissions savings. Unlike the case of slag, the competing producers (electricity utilities) do not receive free allocation.

The steel plant generates and sells electricity and has the following profit function:

$$Max \quad \Pi_{s_i} = p_s q_{s_i} + p_{el} q_{el_i} - c_{s_i}(I,O) - c_{el_i}(I,O) - p_e e_{s_i}(I,O) - p_e e_{el_i}(I,O) + p_e a_i \tag{18}$$

with free allocation being scope adjusted for the additional electricity output, $a_i = q_{s_i} BM_s + \gamma q_{el_i} BM_{el}$.

The electricity generator faces the following profit maximization problem:

$$Max \quad \Pi_{el_k} = p_{el} q_{el_k} - c_{el_k}(I,O) - p_e e_{el_k}(I,O) \tag{19}$$

where he is not eligible for free allocation.

Assuming equal cost and emission functions, the scope adjustment for the electricity by-product for the steel plant reduces its marginal costs of electricity generation compared to the marginal production costs of the electricity plant. Equation 20 shows on the left hand side of the marginal costs of the steel producer and on the right hand side the marginal costs faced by the electricity generator:

$$\frac{\partial c_{el_i}}{\partial q_{el_i}} + p_e \frac{\partial e_{el_i}}{\partial q_{el_i}} - \gamma q_{el_i} BM_{el} = \frac{\partial c_{el_k}}{\partial q_{el_k}} + p_e \frac{\partial e_{el_k}}{\partial q_{el_k}} \tag{20}$$

This equality however only holds if there is no scope adjustment, i.e. $\gamma = 0$. A zero scope adjustment thus provides a level-playing field for the output production of the two firms. Equation 20 thus shows that it is not necessary to adjust the scope for the indirect emissions savings made by by-products if the price of the competing good internalizes carbon costs. Such adjustment would lead to unfair competition among firms.

4.5. Emerging principles for benchmark design

In the previous subsection, we investigated the effect of scope adjusted benchmarks. The four cases examined lead to two main principles around accounting for indirect emissions in benchmarking. If carbon costs are internalized in the price of an input or output, or where competing products do not receive free allocation, do not adjust the scope of the benchmark. If instead carbon costs are not internalized in the price of an input or output, an adjustment should be made to the benchmark scope in the following way: deduct free allocation for the indirect emissions in purchased inputs from off-site facilities; and give additional allocation for production of desirable by-products if the competing producers also receive free allocation. If explicit adjustments are made for by-products, main product benchmark should be adjusted, to remove implicit attribution to these by-products. Alternatively, to ensure fair competition, free allocation for all the producers could be cancelled altogether.

This analysis shows that systematically reflecting the scope of emissions in benchmarks establishes comprehensive incentives to improve carbon efficiency of production. It removes adverse effects of outsourcing upstream production and provides an option to cover incremental costs of producing by-products, which can be used as low-carbon substitutes in other production processes. Harmonizing the scope of emissions coverage in benchmarks across trading schemes will facilitate fair comparisons and cooperation to broaden the basis for setting benchmarks. Moreover, widening the scope of emissions covered in benchmarks expands options for cost effective mitigation whether on-site or off-site.

5. Quantifying avoided distortions through scope adjusted benchmarks

What is the likely magnitude of the distortions corrected by the proposed scope adjustment? In this section, we use actual production data from an integrated blast furnace plant[16] and the example of the EU ETS to quantify the distortions which are currently arising from the design of free allocation. Table 1 shows the plant level emissions, free allocation under current EU ETS benchmarks, and free allocation under scope adjusted benchmarks for an input and an output case.[17]

In the input case, we consider the use of off-site versus on-site coke, similar to the theoretical case discussed above. We compare a plant that buys all coke input off-site with a plant using only coke from on-site production. The on-site emissions are lower for a firm which outsources coke production. Under the current EU ETS benchmarks, which are based on historic production volumes and assumes on-site coke production, there is thus an incentive to outsource coke production after free allocation levels are determined and set for a certain period of time. In doing so, firms then receive more free allocation than they have emissions, and are able to sell the unused certificates on the market. Moving towards output-based allocation reduces these disincentives[18] and requires even more so a timely adjustment of benchmarks to be based on the true scope of a production facility. The scope adjusted benchmarks thus neutralize dis-/incentives for out-/in-sourcing input production by allocating an appropriate level of free certificates. The calculation in Table 1 shows that whether a firm is choosing to buy coke off-site or to produce it on-site, the difference in free allocation per tonne of output and the firm's emissions per tonne of output is the same.

In the output case, we consider the additional production of a by-product versus a business-as-usual (BAU) production. We compare a BAU-plant with a plant producing the double amount of slag.[19] Increasing the slag output is however physically linked to an increased level of emissions. Under the current EU ETS scheme, both firms receive the same amount of free allocation. The scope adjusted benchmark grants additional emission certificates to the firm which produces more slag, based on amount of slag being produced. The additional free allocation certificates are shifted

[16] Production data for an actual integrated blast furnace plant is taken from Buttiens et al. (2016) (see Appendix C, Table C1) to calculate adjusted benchmark values per metric ton of hot metal.

[17] Note that the plant forming the basis of these calculations does not operate at the benchmark level in terms of CO_2-efficiency. Therefore the free allocation under current EU ETS benchmarks does not cover all firm's emissions.

[18] As free allocation is contingent on continued production of on-site coke.

[19] The production capacity of slag of different BF plants is taken from Buttiens et al. (2016), where an average BF plant produces 0.3 metric tons of slag/metric ton of hot metal and the maximum amount of slag production of a BF plant is considered to be 0.6 metric tons of slag/metric ton of hot metal.

Table 1: Free allocation per metric ton of hot metal with unadjusted and adjusted benchmarks

Case	Emissions	Allocation under EU ETS BM	Allocation under scope adjusted BM	Allocation for cement producer	Total allocation for steel and cement producer
1: Input case					
Firm outsourcing coke production	1.35	1.41	1.33		
Firm insourcing coke production	1.43	1.41	1.41		
2: Output case					
Firm producing BAU-amount of slag	1.43	1.41	1.41	0.69	2.10
Firm producing double amount of slag	1.60	1.41	1.64	0.46	2.10

Note: The calculations are normalized to one metric ton of hot metal output or one metric ton of cement, respectively. Underlying plant level data is taken from Buttiens et al. (2016). Benchmark values are taken from the EU ETS: BM hot iron 1.328t/t CO_2; BM clinker 0.766t/t CO_2; BM coke 0.286t/t CO_2. The last column shows the total allocation for one metric ton of hot metal and one metric ton of cement.

away from the cement producer to the steel producer: As the cement producer, in the second step, uses an input with internalized carbon prices, his free allocation is reduced. Total free allocation is thus constant as shown in the last column of table 1. This last column represent the total amount of free allocation granted for the production of one metric ton of cement and one metric ton of hot metal. In the case of an increased slag production, we assume that this slag is fully used in cement production, thus lowering the emission intensity of the cement production. In the extreme case of a doubling of slag production, the results in Table 1 for the scope adjusted benchmarks show that the firm would receive more free allocation than its actual emissions which is a result from the fact that slag production is more carbon efficient than clinker production. Whether firms will increase their slag production up to such a point where free allocation exceeds their actual emissions is however uncertain as additional costs, such as energy costs, will be incurred.

In a further step, we calculate how profits will be affected when firms switch from out-sourcing coke production to in-sourcing and from producing a BAU-amount of slag to doubling the slag production. We calculate the change in contribution margins, i.e. selling price per unit minus variable costs per unit, for the two switching cases for the scenario of undergoing the switch in the current EU ETS system and for the scenario of scope adjusted benchmarks. In order to get a sense of the magnitude of distortions in the current EU ETS and what effect a switch to scope adjusted benchmarks would imply, we compare the difference of the change in contribution margin under EU ETS and the change in contribution margin under the scope adjusted benchmarks, to the profit margin of steel production. This percentage is displayed in Table 2.[20] In the input

[20] We assume a 5% margin and a 20EUR/t CO_2 price, and take hot metal, clinker and coke benchmarks from the

case, purchasing coke from off-site plants reduces the contribution margin, primarily due to the high coke prices underlying our model. The incentive to buy off-site coke is further reduced under scope adjusted benchmarks. In the output case, the contribution margins are higher for producing additional slag. This incentive is reinforced under scope adjusted benchmark. The magnitude of these effects are economically important as shown in the last column - the changes in contribution margins account for up to one third of the profit margin of one tonne of hot metal. This change in the contribution margin however has to contribute to recovering possible additional fixed costs from switching production plans. Nonetheless, scope adjustment of benchmarks for inputs and by-products that do not have carbon costs internalized, gives economic incentives for firms in terms of profits for choosing less inputs without internalized carbon costs and producing more desired by-products.

Table 2: Changes in contribution margin (i.e. selling price minus variable costs) in case of scope adjusted benchmarks

Case	Change in margin under EU ETS BM	Change in margin under scope adjusted BM	Difference of change in margins relative to profit of one metric ton of hot metal
1: Firm buying all off-site coke compared with firm producing on-site coke	-22.73 EUR/t	-24.43 EUR/t	-10.59 %
2: Firm producing double amount of slag compared with firm producing average amount of slag	3.04 EUR/t	7.63 EUR/t	28.69 %

Note: The calculations are normalized to Euros per one metric ton of hot metal output. Underlying plant level data is taken from Buttiens et al. (2016). The underlying benchmark values are taken from the EU ETS: BM hot iron 1.328t/t CO_2; BM clinker 0.766t/t CO_2; BM coke 0.286t/t CO_2. A CO_2 price of 20 EUR/t is used. The calculations of the contribution margin are based on variable costs/savings only, without considering new capital investments (e.g. for a granulator) and assuming a linear production process. Price data is taken from Eurostat, the online database Steelonthenet, and the US Government. A 5%-profit margin is assumed per metric ton of hot metal.

6. Combining scope adjusted benchmarks with downstream consumption charge

As we have shown, applying scope adjusted benchmarks to output based free allocation offers a way to address carbon leakage whilst maintaining incentives for producers to make efficient production choices. However, one key challenge identified with the use of output based free allocation is that, because output based allocation essentially acts as a subsidy for continued production, it leads to the over-production of carbon intensive goods (Fischer, 2001; Fischer and Fox, 2007). As noted, there is limited cost pass through with output based allocation, such that consumers do not observe the carbon price signal in the final product prices and demand shifts towards lower carbon

EU ETS.

alternatives are largely forgone. The market signal for producers to develop cleaner processes and new, alternative low-carbon goods is hampered.

One proposed solution to activate the demand response mechanism is to combine output based allocation with a carbon consumption charge for basic materials (Ismer et al., 2016; Böhringer et al., 2017). Administratively, this approach works similarly to excise on fuels, alcohol and tobacco. In the case of steel, the steel producers receive free allocation based on a benchmark, and are required to report the quantity of steel produced and sold on domestically. When the steel is sold, such as to a car manufacturer, the liability for the consumption charge is transferred from the steel to the car manufacturer. When the steel is released for final consumption, for example in a form of a car, the vendor is liable for a charge, equivalent to the weight of the steel in the car sold, multiplied by the steel benchmark and the carbon price. The carbon price is thus restored at the final consumption end, and internalized in the price of the final good. [21] In this section, we explore if economic incentives can be fully restored for efficient material production and consumption under emissions trading by combining the scope adjusted upstream benchmarks with a downstream consumption charge.

Figure 3 illustrates the effects of an emission trading scheme combined with benchmark based free allocation and a consumption charge in terms of production costs and supply quantities. The left panel of Figure 3 shows that the introduction of emission pricing increases the marginal costs of clinker production by the marginal cost of emission certificates, shifting the initial supply, S_0, up to S_1. Free allocation reduces the effective marginal costs for producers and thus shifts the marginal cost curve downwards to S_2. As the carbon costs are not fully internalized, the equilibrium supply quantity, Q_1, is larger than under full cost internalization, Q^*, signifying an over-production.

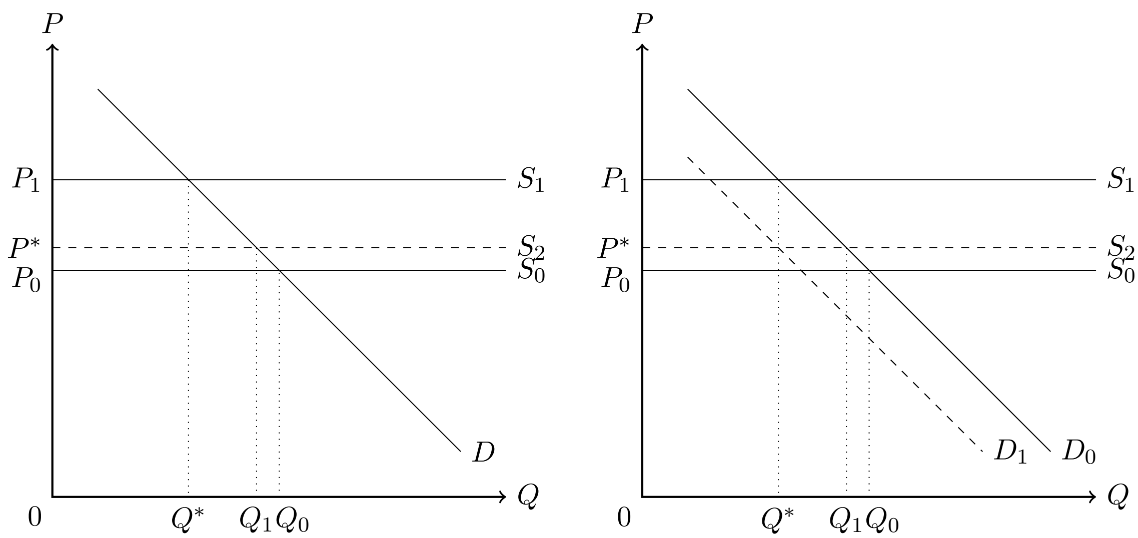

Figure 3: Demand and supply with emission trading (left panel) and consumption charge (right panel)
Note: S_0: no emission pricing= $\frac{\partial c}{\partial Q}$, S_1: full emission pricing=$\frac{\partial c}{\partial Q} + P_e \frac{\partial e}{\partial Q}$,
S_2: emission pricing with benchmark rebate =$\frac{\partial c}{\partial Q} + P_e(\frac{\partial e}{\partial Q} - \frac{\partial BM}{\partial Q})$

Supplementing scope adjusted benchmarks with a consumption charge on basic materials, i.e. on clinker, reduces the demand down to D_1 (Figure 3, right panel), thus re-installing the socially

[21] The liability is waved on steel or cars that are exported, and firm that import carbon-intensive products have to report the weight of for example steel, and take the corresponding liability.

optimal supply of the respective product, Q^*. Looking at the demand side, the initial utility function of the consumer i, U_i, depends on good q_x and good q_y, is twice differentiable, increasing and concave in q_x and q_y, and is subject to a budget constraint:

$$U_i(q_x, q_y) \quad s.t. \quad p_x q_x + p_y q_y = W_i \tag{21}$$

where p_x and p_y are the prices of good X and Y respectively, and W_i is the wealth of consumer i.

Introducing a consumption charge, t, on product X, leads to the total price being considered in the budget constraint of the consumer:

$$U_i(q_x, q_y) \quad s.t. \quad (p_x + t)q_x + p_y q_y = W_i \tag{22}$$

Maximizing the consumer's utility, now leads to a shift of the demand curve in the right panel of Figure 3. Assuming, for simplicity, only one consumer and one firm in the economy, normalizing the price of good Y to one, $p_y = 1$, the new equilibrium quantity of good Q_x in the market equals[22]:

$$MRS_i - t = \frac{\partial c}{\partial q_x} + p_e(\frac{\partial e}{\partial q_x} - \frac{\partial a_i}{\partial q_x}) \tag{23}$$

The equilibrium quantity and price now additionally depend on the consumption charge. If the consumption charge, t, equals the marginal free allocation, $p_e \frac{\partial a_i}{\partial q_x}$, this re-installs a situation of full carbon cost internalization in the market:

$$MRS_i = \frac{\partial c}{\partial q_x} + p_e \frac{\partial e}{\partial q_x} \tag{24}$$

The revenues collected through the consumption charge can substitute revenues otherwise gathered from distortionary charges, thereby creating a double dividend and thus potentially increasing overall welfare of society. Consequently, the combination of output based free allocation and scope adjusted benchmarks with a consumption charge can restore incentives for efficient material production and consumption.

7. Conclusion

This paper revisited emission benchmark designs and critically evaluates them, identifying incentive distortions that occur from the current design of benchmarks. In particular, we ask how the coverage of indirect emissions in the scope of product benchmarks affects firms' decisions on inputs and outputs. In doing so, the paper highlights the importance of well-designed free allocation mechanisms in the context of investment and emission reduction incentives.

From the theoretical analysis of our paper, two main principles for benchmark design emerge. First, where input or output prices do not reflect a carbon price, benchmarks should be adjusted to restore optimal production incentives. Namely, additional allocation for on-site input production should be granted when it replaces off-site inputs that do not have carbon costs internalized. Furthermore, additional allocation for production of desired by-products should be granted if producers of competing products receive free allocation. Second, where carbon prices are reflected in input or

[22] In a market equilibrium, the marginal rate of substitution equals the marginal cost of production. The marginal rate of substitution of the consumer i equals $MRS = \frac{\partial U(q_x,q_y)}{\partial q_x} \frac{\partial q_y}{\partial U(q_x,q_y)}$. We normalize the price of good Y to one. The marginal costs of production of the firm i is based on the maximization of its profit function, $Max \quad \Pi_i = p_x q_{x_i} - c_(I, O) - p_e e(I, O) + p_e a_i$

outputs, where competing products do not receive free allocation, there should be no adjustments through the benchmark allocation. The empirical application in this paper shows that avoiding distortions by adjusting the scope of benchmarks, represents a significant share of firms' profit and is thus able to re-install economic incentives.

The scope adjusted upstream benchmarks presented in this paper have even more potential to incentivize low-carbon investments and innovation when combined with a downstream consumption charge, as shown in this paper. Next to re-installing socially optimal supply levels of basic materials, this combination of policy measures is able to trigger demand side responses to create a long-term investment environment for firms, paving the way for radical innovations. We show that the implementation of a consumption charge restores socially optimal supply quantities of materials without deterring overall welfare. The revenue generated through the consumption charge might then be redistributed e.g. as public innovation funding.

Our findings for benchmarking in the steel sector show that it is not necessary to have a global carbon price in order for carbon pricing to be effective for basic materials sectors that are exposed to carbon leakage risk. Instead, well designed and targeted anti-leakage measures, including benchmarking based free allocation, can be implemented in such a way that the carbon price signal can be easily incorporated into the strategic choice for companies.

Going forward, as technologies and emissions trading schemes evolve, benchmarks can be a focal point for global cooperation across emissions trading systems to ensure innovation incentives are retained. So far, all emission trading schemes faced the same challenge of developing principles for incorporating breakthrough technologies into benchmark design. Global cooperation on benchmarks might not only offer a larger sample size to draw on for the calculation of benchmarks but also offers room for developing best practice guidelines.

There are two remaining challenges when implementing scope adjusted benchmarks in practice. First, the determination of whether carbon costs are internalized or not in a setting without output based allocation. Often in practice, carbon costs are only partially internalized in these settings. In order to illustrate the functioning of scope adjusted benchmarks, we choose to consider electricity as a product with fully internalized carbon costs. One way of dealing with partial carbon cost pass through might be to set categories of low, medium, and high carbon cost pass through with respective threshold values. Similar to the assessment of carbon leakage risk, the categorization of carbon cost pass through levels should be dealt with by policy makers. Second, market power that might limit the effect of adjusted benchmark incentives. Parts of the basic materials sector are characterized by an oligopolistic market structure. According to steel producers, they are, for example, dependent on electricity generators to sell their electricity or on cement producers to sell their granulated slag. Thus, there might be additional policies needed to incentivize the use of low-carbon substitutes.

Appendix A

Table A1: Design aspects of emission benchmarks across international ETSs

	Type of benchmark	Corresponding activity level	Benchmark setting	Scope of emissions covered
EU (Phase 3)	52 product benchmarks, heat benchmark and fuel benchmark as fallback	Historic activity level in baseline year	Average emissions intensity for the top 10% most efficient installations within each sector	Direct emissions only. Share of indirect electricity emissions subtracted in some cases.
California	28 product benchmarks, fuel use benchmark	Recent output level updated annually, or historic baseline level for fuel benchmarks	Allocates 90% sector average emission intensity	Direct and indirect
New Zealand	42 product benchmarks, electricity usage benchmark	Recent output level updated annually	Industry average	Direct; indirect associated with electricity consumption
South Korea	3 sectors product benchmark, heat/fuel benchmark	Historic activity level in baseline year	Weighted average emissions intensity of eligible entities (not installations)	Direct; indirect emissions from large electricity consumers
China (pilots)	42 industry benchmarks, 79 benchmarks for sub-categories	Actual output level with frequent updating	Tightest of seven benchmarks considered (including EU benchmark, energy efficiency benchmark)	Direct; indirect emissions from electricity (and heat) consumption

Sources: European Commission (2011), Board (2011), CA Environmental Protection Agency (2010), NZ Ministry for the Environment (2002), ICAP (2016a), ICAP (2016b), Qing (2015)

Appendix B

The cement producers chose the quantity of clinker and slag inputs to maximize their profit function:

$$Max \quad \Pi_{ce_i} = p_{ce}q_{ce_i} - p_{cl}q_{cl} - p_{sl}q_{sl} - c_{ce_i}(I,O) - p_e e_{ce_i}(I,O) \tag{25}$$

Partially differentiating this with respect to the clinker input q_{cl_i} and the slag input q_{sl_i}, while using the optimizing conditions of $\frac{\partial \Pi_{ce_i}}{\partial q_{cl_i}} = 0$ and $\frac{\partial \Pi_{ce_i}}{\partial q_{sl_i}} = 0$ gives the following conditions by which the cement producer bases input decisions, namely equalizing marginal revenue of each input to its marginal costs:

$$\frac{\partial q_{ce_i}}{\partial q_{cl_i}} p_{ce} = p_{cl} + \frac{\partial c_{ce_i}}{\partial q_{cl_i}} + p_e \frac{\partial e_{ce_i}}{\partial q_{cl_i}} \quad and \quad \frac{\partial q_{ce_i}}{\partial q_{sl_i}} p_{ce} = p_{sl} + \frac{\partial c_{ce_i}}{\partial q_{sl_i}} + p_e \frac{\partial e_{ce_i}}{\partial q_{sl_i}} \tag{26}$$

Keeping in mind that $q_{cl} = \beta q_{sl}$, the marginal product of slag can be expressed in terms of the marginal product of clinker: $\frac{\partial q_{ce_i}}{\partial q_{sl_i}} = \frac{1}{\beta}\frac{\partial q_{ce_i}}{\partial q_{cl_i}}$. Plugging this into the second equation of equation 26, solving for the marginal revenue of clinker and plugging this into the first equation of Equation 26, yields the following equality:

$$p_{cl} + \frac{\partial c_{ce_i}}{\partial q_{cl_i}} + p_e \frac{\partial e_{ce_i}}{\partial q_{cl_i}} = \beta(p_{sl} + \frac{\partial c_{ce_i}}{\partial q_{sl_i}} + p_e \frac{\partial e_{ce_i}}{\partial q_{sl_i}}) \tag{27}$$

Equation 27 depicts the marginal costs of clinker on the left side and the marginal costs of slag on the right side, multiplied by the conversion factor of slag to clinker. The equations show that the cement producer will thus only be willing to pay the service equivalent price for slag. Without the scope adjustment to the free allocation to the slag producing steel plant (Equation 15), for a given price, the steel producer is less willing to produce slag, thus slag is undersupplied.

Appendix C

Table C1: Production data of relevant in- and outputs of a Blast Furnace plant

Product	Value per t of hot metal
Inputs	
Coke[1]	0.297 t
Natural Gas	1.187 GJ
Coking coal	0.182 t
Outputs	
Pig iron/ Hot metal	1
CO2	1.433 t
Slag	0.292 kg

Source: Buttiens et al. (2016)

[1] This reflects the amount of coke produced in an integrated BF plant, the appropriate input of a BF plant is coking coal.

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