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Is broader trading welfare improving for emission trading systems?*

Xianling Long[†] Nicolas Astier[‡] Da Zhang[§]

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Emission trading systems are cornerstone policies to reduce carbon emissions. Although economic intuition suggests that broader allowance trading should always be welfare improving, this paper proves that view can be wrong. Under an increasingly popular type of emissions trading scheme – tradable performance standards (TPS), multiple narrow markets can decrease emissions relative to a single unified market, so that restricting trade does not always harm welfare. We show analytically that, when intensity benchmarks are heterogeneous within a sector, this result can hold even if the well-known “implicit output subsidy” does not arise. Finally, we provide evidence that this concern is not a mere theoretical possibility but can actually be of high practical relevance. Using a general equilibrium model of China’s TPS for 2020–2030, we show that broader trading results in significantly higher emissions (up to 10%), and decreases welfare relative to narrower markets when the social cost of carbon exceeds \$91/tCO₂.

Keywords: carbon pricing; tradable performance standards; cap and trade; trading scope; social cost of carbon

JEL: D58, D61, H23, Q52, Q54, Q58

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1 Introduction

Emission trading systems (ETS) are currently the main policy instrument used to mitigate climate change. Under an ETS, the government sets rules to allocate emission allowances, and firms can trade these allowances in a market. The market price for allowances is then determined by the usual supply and demand dynamics. If a firm can reduce its emissions at a cost lower than the market price for allowances, it will choose to reduce emissions and sell its unused allowances. Conversely, if its abatement cost exceeds the market price for allowances, it will choose to purchase additional allowances instead of reducing emissions.

Allowance trading decreases the economy-wide cost of achieving emission reductions by directing abatement efforts to firms that can make these efforts at the lowest cost. Intuitively, expanding allowance trading scope, that is, implementing a broad market rather than several narrowly defined markets,¹ increases the set of possible re-allocations, and thus generates higher “gains from trade”. Standard economic intuition therefore suggests that broader trading under an ETS is inherently welfare-improving. This paper challenges this commonly held view for a specific type of ETS: tradable performance standards.

There are indeed two main types of ETS: mass-based ETS and intensity-based ETS. In a mass-based ETS (i.e., cap & trade (C&T)), the total number of allowances allocated to firms is pre-determined, forming a fixed aggregate emission cap, regardless of the scope of allowance trading. In contrast, an intensity-based ETS, such as a tradable performance standards (TPS), operates differently. Under a TPS, which is the focus of this paper, emission allowances are determined based on emission intensities, i.e., the emissions per unit of output. Specifically, each firm is assigned an emission intensity “benchmark”, and the number of allowances allocated to the firm is the product of its benchmark and its level of output. Such an allowance allocation rule implies that the total number of allowances depends on firms’ production decisions, and is thus endogenous. Indeed, facilities can influence their allowance allocation by adjusting their output levels. This endogeneity results in an “implicit subsidy” to production in TPS systems, hampering their cost-effectiveness relative to C&T mechanisms (Fischer, 2001; Fischer et al., 2017; Bushnell et al., 2017; Karplus and Zhang, 2017; Zhang et al., 2018; Pizer and Zhang, 2018; Goulder et al., 2022; Wang et al., 2022).

¹We use the expression “broader trading” to refer to an expansion of the scope of allowance trading in an ETS, rather than an increase in emission or sectoral coverage. In other words, sectoral coverage is identical under both “narrow” and “broad” trading, but allowances are fungible across sectors only in the latter case.

One example of TPS is China’s national emissions trading system. Launched in 2021, it has become the world’s largest carbon ETS, doubling the amount of CO₂ emissions covered worldwide by some form of carbon pricing. As of mid-2023, China’s TPS covers only the electricity sector. However, the Ministry of Environment and Ecology – the ministry responsible for the design and implementation of the program – is actively working on designing the next phases of the TPS, during which it is expected to expand to more sectors, such as cement, aluminum and iron& steel production. In the next phases, the issue of trading scope will therefore become of practical relevance. In addition, many ETSs, including those in California,² Canada,³ the European Union,⁴ the United Kingdom,⁵ and New Zealand,⁶ incorporate provisions for updating the allocation of free allowances based on firms’ actual output levels, therefore exhibiting somewhat similar features as a TPS.

This paper asks whether broader allowance trading is necessarily welfare-improving under a TPS. We tackle this question using both analytical and numerical approaches. We consider an economy consisting of multiple sectors, where each sector is composed of firms with different emission intensities producing a homogeneous good. We compare the equilibrium outcomes under two scenarios: inter-sectoral allowance trading, which involves a single unified (“broad”) allowance market, and intra-sectoral allowance trading, which involves multiple sector-specific (“narrow”) markets. Importantly, since the total number of allowances is endogenous under a TPS, the equilibrium aggregate emissions may be higher with a broad allowance market than with several narrower markets. Therefore, expanding the scope of allowance trading is welfare-improving only if the private gains from broader trading exceed the additional environmental costs (if any).

We first show analytically that broader allowance trading may indeed *increase* aggregate emissions relative to narrower trading. This is likely to occur when sectors with larger tar-

²See <https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/allowance-allocation/allowance-allocation-industrial> (Accessed 5/28/2023).

³See <https://www.gov.uk/government/publications/participating-in-the-uk-ets/participating-in-the-uk-ets> (Accessed 5/28/2023).

⁴See https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/revision-phase-4-2021-2030_en (Accessed 5/28/2023).

⁵See <https://www.gov.uk/government/publications/participating-in-the-uk-ets/participating-in-the-uk-ets> (Accessed 5/28/2023).

⁶See <https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/ets/participating-in-the-nz-ets/overview-industrial-allocation/> (Accessed 5/28/2023).

geted emission reductions are the ones facing smaller challenges in reducing them. In such cases, although inter-sectoral trading decreases private compliance costs, it can ultimately reduce social welfare compared to intra-sectoral trading. Indeed, the impact of broader trading on welfare then depends on the value of the social cost of carbon (SCC): at a sufficiently high SCC, increased environmental costs will outweigh private gains from trade. Furthermore, we find that the comparison between inter-sectoral and intra-sectoral trading is highly influenced by the degree of heterogeneity in emissions intensity benchmarks within each sector. A smaller degree of heterogeneity in benchmarks increases the likelihood of broader trading to be welfare-improving. Our analytical results highlight the key insight that, under a TPS, expanding the scope of allowance trading does not guarantee welfare improvements, especially in situations where multiple benchmarks co-exist within each sector.

We then employ a dynamic general equilibrium model to assess the practical relevance of our analytical findings. The general equilibrium structure of our model is designed to capture the interactions among production sectors, households, and the government in the context of China’s nationwide TPS. Although China’s nationwide TPS currently covers only the electricity sector, its coverage is expected to expand in subsequent implementation phases. Allowance trading scope will therefore shortly become a relevant issue. By solving this model numerically, we estimate that the present value of the private cost⁷ of the TPS for 2020-2030 would amount to \$82 billions under the inter-sectoral allowance (i.e., “broad”) trading scenario, 30 percent lower than the cost under the intra-sectoral (i.e., “narrow”) trading scenario.⁸ However, inter-sectoral trading increases carbon emissions relative to intra-sectoral trading. Specifically, inter-sectoral allowance trading increases emissions by 313 million tCO₂ relative to intra-sectoral trading over the 2020-2030 period. The annual increase in emissions due to broader trading is about 2-9% of the annual total emission reductions. The decrease in environmental benefits resulting from broader trading exceeds the reduction in private costs when the SCC is above \$91/tCO₂.⁹ For such values of the SCC, inter-sectoral trading decreases social welfare relative to intra-sectoral trading.

Furthermore, our numerical results confirm the critical role of the within-sector hetero-

⁷The present value is calculated with a discount rate of 5%.

⁸The model spans from 2020 to 2030, covering all three planned phases of China’s TPS. The first modeling year is 2020 because the first compliance period depends on emission data in 2020, although the first trading period starts in 2021

⁹The SCC is in 2020 value and is assumed to increase by 3% annually. If we assume instead a constant SCC, the threshold value is \$111/tCO₂.

geneity in benchmarks for a TPS. When uniform within-sector benchmarks are implemented, the SCC threshold increases to \$114/tCO₂, indicating that a smaller variation in the values of benchmarks makes broader trading more likely to improve welfare. When comparing different benchmark designs, we find that the uniform-benchmark case is the most cost-effective approach to reducing emissions.

This paper relates to several strands of literature. First, many studies rely on analytical models and/or numerically solved general equilibrium models to assess the cost-effectiveness of alternative policies to first-best emission pricing (e.g. [Goulder et al. \(2016, 2022\)](#) among many others). Among these studies, a growing body of work on intensity-based ETS (i.e., TPS), and more broadly, rebating emissions pricing revenues that includes output-based allocation ([Böhringer and Lange, 2005](#); [Böhringer et al., 2022](#); [Fischer et al., 2022](#)). Existing studies on these policies predominantly use a single-sector framework ([Fischer and Springborn, 2011](#); [Becker et al., 2020](#); [Geng and Fan, 2022](#); [Goulder et al., 2022](#); [Ma and Qian, 2022](#); [Wang et al., 2022](#); [Yu et al., 2022](#)). [Goulder et al. \(2023\)](#) do investigate a TPS that covers multiple sectors, but assume inter-sectoral trading. Therefore, the impacts of trading scope under TPS have received little prior recognition. In addition, this paper relates to the literature on expanding emissions trading systems through linkages across jurisdictions or sectors. Several studies within this literature discuss the private gains that result from broader allowance trading. For example, [Böhringer et al. \(2017\)](#) suggest that the tradability of allowances across sectors can mitigate the inefficiencies of intensity standards compared to Pigouvian taxation. Other studies discuss the impacts of market linkage on emissions. Some of them specifically focus on TPS. [Fischer \(2003\)](#) uses a theoretical model to explore the consequences of linking a TPS and a C&T, finding that trading can potentially increase emissions. Similarly, [Bushnell et al. \(2017\)](#) examine the incentives of U.S. states to integrate carbon markets and find that linking intensity-based allowance markets across states may increase emissions. Moreover, there is a body of literature that investigates the effects of market linkage on emissions in the context of C&T. While aggregate emissions during a compliance period are determined exogenously in a C&T, linking allowance markets can have intertemporal impacts on emissions. [Holtmark and Midttømme \(2021\)](#) find that integrating allowance markets across countries can reduce emissions if countries strategically adjust their future emission caps in response to market linkage, while [Lapan and Sikdar \(2019\)](#) argue that linking allowance markets across countries weakens the incentives for tightening national emission caps.

This work makes several important contributions. First, although the limitations of a TPS have been pointed out early on (Helfand, 1991), they have been usually assessed against either business-as-usual or Pigouvian taxation (or equivalently, a C&T). Here, we instead compare two different designs of a TPS: broad vs narrow trading, in the spirit of Bushnell et al. (2017).¹⁰ Second, the main mechanism behind the previously studied inefficiencies of a TPS is the so-called “implicit output subsidy”: firms respond by increasing overall output, which may result in higher emissions. Our theoretical analysis instead focuses on the inefficiencies induced by heterogeneous subsector-specific intensity benchmarks.¹¹ In particular, our analytical results show that removing trade restrictions can increase overall emissions even when sector-level output remains constant, that is, when the main inefficiency induced by the “implicit output subsidy” does not arise. Third, although Fischer (2003) and Bushnell et al. (2017) also find that trading can potentially increase emissions under a TPS, we further examine the conditions under which expanding trading scope is welfare improving and the implications of different benchmark designs within and across sectors, which deepens our understanding of the underlying mechanisms. Fourth, we explore the roles of demand elasticity, heterogeneity in abatement costs, market power and political acceptability in comparing broad versus narrow trading, which are largely overlooked in previous studies. Fifth, and most importantly, a theoretical possibility is not always of practical relevance. For example, Holland et al. (2009) show that low carbon fuel standards can, in theory, result in an increase in net carbon emissions but are, in practice, very unlikely to do so. In contrast, our empirical exercise suggests that the inefficiencies we highlight do matter significantly in the context of the world’s largest ETS – the Chinese TPS. Our results therefore provide valuable insights for the ongoing policy discussions surrounding the design and implementation of intensity-based ETSs.

Finally, it is worth stressing that our findings have important policy implications. Indeed, Chinese policymakers still have to make crucial decisions regarding the future of China’s TPS, such as the scope of allowance trading (intra-sectoral vs inter-sectoral) and the determination of benchmarks. We offer both an analytical framework and a numerical model to help understand when broader trading increases social welfare, depending on the choice of intensity benchmarks and the SCC. These insights can inform the decision-making process of

¹⁰In our setting, a sector formally plays a similar role as a US State in Bushnell et al. (2017).

¹¹In contrast, Bushnell et al. (2017) assume that (implicit) emission benchmarks are uniform within each US State. Our setting is instead formally similar to fuel-economy low carbon fuel standards in Holland et al. (2009), with the important difference that heterogeneous benchmarks are endogenous policy parameters, not exogenously given technology parameters.

TPS. Furthermore, our findings have implications for other ETSs whose designs share some features of a TPS in terms of allowance allocation, including the other ETSs aforementioned. To some extent, these systems exhibit similar behaviors to TPS regarding the impacts of trading scope. Therefore, our study contributes to a broader understanding of the implications of trading scope in ETS, which can inform the design of such systems globally.

The remainder of this paper is organized as follows. Section 2 provides a brief overview of China’s TPS. Section 3 presents the analytical model we develop to analyze the impacts of TPS under various trading scopes. Section 4 employs a general equilibrium model to numerically quantify these impacts within the context of China’s TPS. Section 5 concludes.

2 Background

In 2009, during the United Nations Climate Change Conference held in Copenhagen, China announced its carbon emission targets for 2020 and 2030. Subsequently, in 2015, during the conference in Paris, China further emphasized its commitment to combat climate change by setting ambitious goals in terms of emission reductions. To meet these targets, China has first implemented several pilot programs for carbon trading mechanisms at the provincial and municipal levels. After a decade of experimenting with and learning from these pilots, China launched its nationwide ETS in 2021. China’s ETS is a crucial component of its strategy to achieve carbon neutrality by 2060.

In contrast to conventional mass-based ETS (i.e., C&T), China’s nationwide program, as well as some of its pilot programs, are intensity-based ETS (i.e., TPS). China’s TPS is being implemented in multiple phases. The first phase covers only the fossil-based electricity sector,¹² which is responsible for more than 40 percent of the country’s total CO₂ emissions. Given the high heterogeneity in technologies and emission intensities within the electricity sector (e.g. coal-fired power plants vs renewables), the TPS uses four distinct benchmarks tailored to different technology categories. The second phase of the TPS is expected to begin in late 2023. It will expand the scope of the program to include the cement and aluminum sectors, as well as possibly the iron & steel sector. Following the second phase, a third phase

¹²It’s important to note that the electricity market in China has been undergoing continuous reforms since the end of the state monopoly in 1985. While the market is partially regulated, recent reforms have allowed for greater market determination of electricity prices, although some fixed amounts of electricity are still sold at government-administered prices. In the numerical model used in this paper, these market reforms and the partially regulated nature of the electricity market are taken into account.

is expected to begin around 2026. This phase may extend the TPS to additional sectors, such as pulp and paper, non-metal products (including ceramics, bricks, and glass), non-ferrous metals (including copper and tin production), raw chemicals (including ethylene, methanol, ammonia, and various synthetic materials), and oil refining (including gasoline and diesel production). The Ministry of Environment and Ecology is actively working on the design of the later phases of the TPS, which will expand the program’s coverage to additional sectors. As part of this design process, decisions need to be made regarding the provisions for allowance trading and the design of intensity benchmarks.

3 Analytical model

In this section, we study analytically the impact of trading scope under a TPS in terms of private costs and environmental benefits. After introducing our framework and notations in Section 3.1, we provide some graphical intuitions in Section 3.2. We then derive our main results in Section 3.3 and highlight the role of the heterogeneity of within-sector benchmarks in Section 3.4. Finally, we discuss the policy implications and limitations of our simple framework in Section 3.5.

3.1 Framework

3.1.1 Assumptions and notations

We define a sector as a set of firms that compete to sell a homogeneous good. We index sectors by i (as “industry”) and assume that the total demand for the commodity produced by sector i is inelastic and equal to Q_i . This assumption is primarily made to simplify the exposition. We discuss how our main results would carry over to a setting with elastic demand in Section 3.5, derive the corresponding analytical expressions in Appendix A, and model demand as being elastic in our numerical section.

Sector i is composed of N_i firms with identical private supply cost functions:

$$c_i(q, a) \equiv \frac{1}{2} \left[N_i q^2 + \frac{q}{\mu_i} a^2 \right] \quad (1)$$

where q is the quantity produced and a the abatement effort of the firm (see below). We assume that N_i is large enough so that firms behave as price-takers.¹³ We extend our frame-

¹³We include N_i in the cost function of firms to make the aggregate supply cost function of the industry

work to account for market power in Appendix C .

Firms emit carbon dioxide. Its social cost is assumed to be exogenous and equal to t^* . The emissions of a given firm are assumed to be proportional to its output, and firms have the ability to invest in an abatement technology a . Indexing firms by j , they are characterized by heterogeneous initial carbon emissions intensities β_j .¹⁴ The carbon emissions e_j from firm j are then:

$$e_j(q, a) \equiv (\beta_j - a)q \quad (2)$$

Note that we assume that firms are heterogeneous in their initial carbon intensities β_j , but that the abatement cost functions – as influenced by the parameter μ_i – are homogeneous within a sector. We discuss within-sector heterogeneity in abatement cost functions in Appendix B as well as in our numerical simulations.¹⁵

Finally, we assume that each sector can be divided into subsectors. Subsectors reflect the fact that the homogeneous good traded in the sector may be produced using different technologies involving different carbon intensities. For example, the electricity sector may be divided into the coal-fired, gas-fired, and oil-fired subsectors. Within a subsector, firms' carbon intensities vary less, compared to firms across different sub-sectors. Each firm is assumed to belong to a single subsector, and we index subsectors by s . We denote with n_s the number of firms that belong to subsector s .

We use i to denote both a sector and the set of subsectors that compose it. For example, we have:

$$\sum_{s \in i} n_s \equiv N_i \quad (3)$$

Similarly, s will denote both a subsector and the set of firms that compose it. Figure 1 clarifies how to interpret our notations using a simple example.

independent of N_i .

¹⁴Lyubich et al. (2018) highlights (in the case of the United States) that within-sector emissions intensity can be very heterogeneous, even when sectors are narrowly defined.

¹⁵In particular, we show in Appendix B that, in the polar case where firms have uniform initial carbon intensities but heterogeneous abatement opportunities, a closed-form solution can also be derived for the case of a single sector under TPS. The obtained formula is however much less tractable, and thus does not generalize easily to multiple sectors. Hence, we focus in the analytical model on the situation where abatement opportunities are homogeneous within a sector.

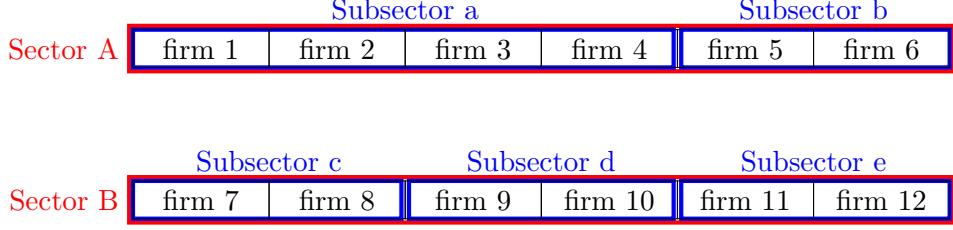


Figure 1: Illustration of sectors, subsectors, and firms. This simple economy has 2 sectors indexed by $i \in \{A, B\}$, each composed of 6 firms ($N_A = N_B = 6$). Sector A has two subsectors $s \in \{a, b\}$ composed of respectively 4 ($n_a = 4$) and 2 ($n_b = 2$) firms. We thus have $A = \{a, b\}$, $a = \{1, 2, 3, 4\}$ and $b = \{5, 6\}$. Similarly, sector B has three subsectors $\{c, d, e\}$ composed of 2 firms each ($n_c = n_d = n_e = 2$). We thus have $B = \{c, d, e\}$, $c = \{7, 8\}$, $d = \{9, 10\}$ and $e = \{11, 12\}$.

We denote with $\bar{\beta}_s$ the average initial carbon intensity of a given subsector s :

$$\bar{\beta}_s \equiv \frac{1}{n_s} \sum_{j \in s} \beta_j \quad (4)$$

We further denote with σ_s^2 the variance of initial carbon intensities within that subsector:

$$\sigma_s^2 \equiv \frac{1}{n_s} \sum_{j \in s} (\beta_j - \bar{\beta}_s)^2 \quad (5)$$

Finally, for any variable X_s defined at the subsector level with $s \in i$, we denote with $\langle X \rangle_i$ its weighted average at the sector level, where each subsector is weighted by its number of firms:

$$\langle X \rangle_i \equiv \frac{1}{N_i} \sum_{s \in i} n_s X_s \quad (6)$$

For example, $\langle \bar{\beta} \rangle_i$ corresponds to the average carbon intensity of sector i .

3.1.2 Welfare metric

Our analytical framework is a partial equilibrium model. Social welfare SW may thus be measured as:

$$SW = GCS - PC - EC \quad (7)$$

where GCS denotes gross consumer surplus, PC the total private cost of firms and EC the total environmental cost.

Under our simplifying assumption that demand is inelastic, gross consumer surplus is constant. Changes in social welfare ΔSW can then be measured as minus changes in social costs:

$$\Delta SW = -\Delta PC - \Delta EC \equiv -\Delta SC \quad (8)$$

Therefore, we use total social cost SC as our welfare metric. This social cost consists of two terms: private production costs and environmental costs. These latter costs EC are equal to total emissions E times the social cost of carbon t^* . Total social cost SC is then:

$$SC \equiv PC + Et^* \quad (9)$$

and the change in social cost ΔSC following a policy intervention is:

$$\Delta SC = \Delta PC + (\Delta E)t^* \quad (10)$$

Importantly, this expression is linear in t^* . Therefore, if ΔPC and ΔE have opposite signs and do not depend on t^* , whether a policy intervention is welfare-improving or not will depend on whether the social cost of carbon t^* is above or below the threshold $\Delta PC/\Delta E$. Since neither ΔPC nor ΔE depend on t^* in what follows, we will pay particular attention to the respective signs of ΔPC and ΔE .

3.1.3 Tradable performance standard

Under a TPS, allowances are allocated based on an emission intensity benchmark $\hat{\beta}$: firm j producing a quantity q and investing in a level a of abatement (per unit of output) gets a net allowance $(\hat{\beta} - (\beta_j - a))q = (\hat{\beta} - \beta_j + a)q$. This net allowance may be positive or negative. Unused or missing allowances are traded between firms. In equilibrium, each firm holds a net quantity of allowances equal to zero.

We allow emission intensity benchmarks to be subsector-specific and define a “relative stringency” parameter α_s as:

$$\hat{\beta}_s \equiv (1 - \alpha_s)\bar{\beta}_s \quad (11)$$

The smaller α_s , the easier it is for firms in subsector s to beat their intensity standard. For simplicity, we assume that, for all s , $\alpha_s < \epsilon < 1$ where ϵ is small enough so that no firm shuts down in equilibrium.

Allowing benchmarks to be heterogeneous within a given sector is critical because, as we

discuss below, benchmark setting is inherently linked to political acceptability considerations, and may thus be used as a second-best tool to achieve redistributive goals. As an illustration, the current nationwide TPS in China, which covers for now only the electricity sector, uses subsector-specific benchmarks.

3.1.4 Scenarios of interest

Under C&T, the decision variable of the social planner is the emission cap. Total emissions are indeed set exogenously at the level of the cap. Enabling firms to trade allowances across two initially-separate C&T thus does not change aggregate emissions ($\Delta E = 0$). However, broader trading decreases private costs ($\Delta PC < 0$). Therefore, broader trading is welfare improving ($\Delta SC < 0$).

In contrast, under TPS, the government chooses the *vector of intensity benchmarks* and whether allowances can be traded across sectors. In what follows, we therefore fix both the vector of intensity benchmarks and the sectoral coverage of the TPS, and compare two scenarios:

- **Intra-sectoral allowance trading (“narrow” trading):** firms can only trade allowances with firms belonging to their sector. Sector-specific “carbon prices” t_i then emerge.
- **Inter-sectoral allowance trading (“broad” trading):** firms can trade allowances with any TPS-covered firm in the economy. A single economy-wide “carbon price” then emerges.

An alternative approach would be to compare two scenarios with identical total emissions. Since we have $\Delta SC = \Delta PC$ when $\Delta E = 0$, such an approach is appealing because it simplifies welfare comparisons. However, because increasing trading scope changes total emissions, keeping emissions the same would require to use different vectors of intensity benchmarks. Unfortunately, the mapping between the vector of intensity benchmarks and total emissions is not injective: a given level of total emissions may be reached by several vectors of intensity benchmarks. One would thus need to enforce a parametric structure for intensity benchmarks (to collapse them to a one-dimensional parameter), or to explicitly state the objective function that the social planner uses to set intensity benchmarks (e.g. minimize private costs). Both approaches are likely to be inconsistent with the actual decision process followed by policy-makers. Therefore, comparing different scenarios under a fixed vector of intensity benchmarks is a more relevant exercise to inform policy-makers.

3.2 Graphical intuitions

We first illustrate a simple example of why broader trading may increase carbon emissions under a TPS. We consider an economy with two sectors with identical aggregate demands ($Q_1 = Q_2 = Q$). We assume no abatement technology is available (i.e., $\mu_1 = \mu_2 = 0$). Each sector is composed of only two firms, which we treat as subsectors. For simplicity, the distribution of emission intensities is assumed to be identical in both sectors: firm 1 generates no emissions ($\beta_1 = 0$) while firm 2 has a positive carbon intensity ($\beta_2 > 0$). However, we assume that different intensity benchmarks are set between the two sectors. In sector 1, firm i faces a benchmark $\hat{\beta}_i$ with $0 < \hat{\beta}_1 < \hat{\beta}_2 = \frac{\beta_2}{2}$. In contrast, a uniform benchmark $\hat{\beta}_1 \equiv \hat{\beta}_2 = \frac{\beta_2}{2}$ is set in sector 2.

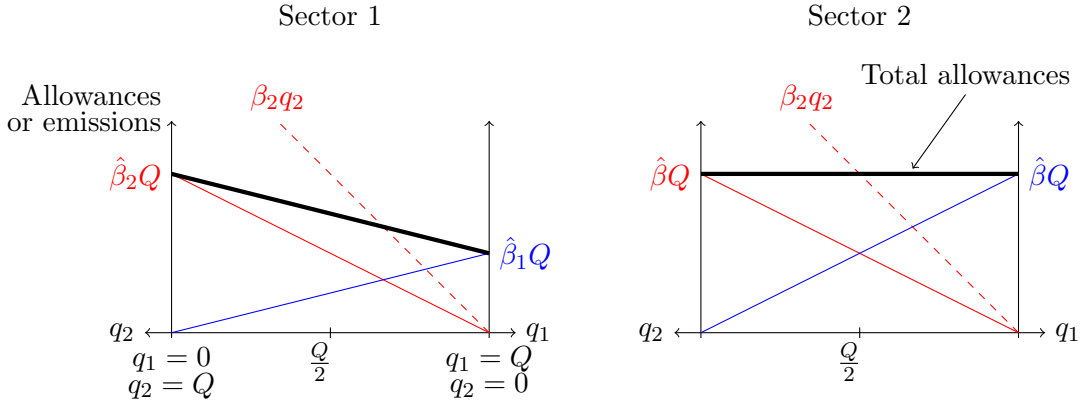


Figure 2: Equilibrium outcomes in the intra-sectoral allowance trading case.

Figure 2 illustrates the outcome of the intra-sectoral allowance trading scenario. Because demand is inelastic, total supply must be equal to Q in both sectors. The x-axis is therefore a segment of length Q , on which we measure the output q_1 of firm 1 from the left-hand side, and the output q_2 of firm 2 from the right-hand side (so that $q_1 + q_2 = Q$). The x-axis segment thus represents the feasible output allocations across the two firms.

Because, in each sector, firm 1 does not generate carbon emissions ($\beta_1 = 0$), the dashed line $\beta_2 q_2$ measures sector-level carbon emissions. Such emissions are equal to zero when $q_2 = 0$ and reach their maximum $\beta_2 Q$ when $q_2 = Q$. The blue and red solid lines represent the amount of allowances allocated to firm 1 ($\hat{\beta}_1 q_1$) and firm 2 ($\hat{\beta}_2 q_2$), respectively. The black thick solid line represents the total allowances allocated in each sector, which are equal to $\hat{\beta}_1 q_1 + \hat{\beta}_2 q_2$. In the intra-sectoral scenario, total allowances must be equal to total emissions for each sector in isolation. The equilibrium output allocation across the two firms of each

sector is therefore pinned down by the intersection of the total emissions and total allowances curves.

We can finally derive the equilibrium allowance price for each sector. This allowance price t is pinned down by the condition that the private marginal costs of each firm must be equal within a sector. For sector 1, this condition is:

$$2q_1 - \hat{\beta}_1 t_1 = 2q_2 + (\beta_2 - \hat{\beta}_2) t_1$$

Since $q_2 = Q - q_1$, this condition may be rewritten:

$$t_1 = 4 \frac{q_1 - \frac{Q}{2}}{\beta_2 - \hat{\beta}_2 + \hat{\beta}_1} = \frac{16}{3} \frac{q_1 - \frac{Q}{2}}{\beta_2}$$

In particular, $t_1 > 0$. By similar reasoning, the equilibrium allowance price in sector 2 is $t_2 = 0 < t_1$.

In the inter-sectoral allowance trading case, allowances can be freely traded across sectors. Since $t_1 > t_2$ in the absence of inter-sectoral trading, sector 1 will become a net buyer of allowances while sector 2 will become a net seller. Sector 2 will increase production of (clean) firm 1 and decrease the production of (dirty) firm 2. Conversely, sector 1 will re-allocate some production from firm 1 to firm 2, since the availability of allowances at a price lower than t_1 increases the private marginal cost of firm 1 and decreases the private marginal cost of firm 2.

From Figure 2, we see that the allowances generated by sector 2 remain constant. In contrast, in sector 1, reallocating production from firm 1 to firm 2, that is moving the equilibrium output allocation to the left, increases the number of allowances (solid black line). As a result, the economy-wide number of allowances, and therefore total emissions, increases when broader trading is introduced.

Finally, we note that an opposite result can also hold. Imagine that we gradually decrease $\hat{\beta}$ in sector 2 towards zero. The intersection of the sector-level allowances and emissions curves then shifts to the right, therefore increasing the allowance price t_2 under the intra-sectoral trading equilibrium. For a stringent enough $\hat{\beta}$, we get $t_2 > t_1$ so that expanding the scope of trading now reallocates production in opposite directions. In particular, firm 1 (resp. firm 2) of sector 1 increases (resp. decreases) production, which in turn decreases the number of allowances created by sector 1 and therefore total emissions.

We conclude that, even in our simple example, the impact of trading scope on total emissions is complex and thus hard to capture with simple intuitions. We therefore turn to solving our analytical model to discuss the obtained closed-form expressions.

3.3 Main results

We present our main analytical results in three steps. We first discuss the impact of broader trading on private compliance costs, then on total emissions and finally on welfare. Because we find the heterogeneity of benchmarks to play an important role, we denote with Ω_i^2 the variance (across subsectors of sector i) of the subsector-specific stringency levels:

$$\Omega_i^2 \equiv \langle (\alpha\bar{\beta})^2 \rangle_i - \langle \alpha\bar{\beta} \rangle_i^2 \quad (12)$$

where, as previously defined, $\alpha_s\bar{\beta}_s \equiv \bar{\beta}_s - \hat{\beta}_s$.

3.3.1 Private cost

Proposition 1 (Broader trading decreases total private costs). *Total private costs under intra-sectoral and inter-sectoral trading are equal to:*

$$\begin{cases} PC_{intra} = \frac{1}{2} \sum_i Q_i^2 + \frac{1}{2} \sum_i \frac{(\langle \alpha\bar{\beta} \rangle_i Q_i)^2}{\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2} \\ PC_{inter} = \frac{1}{2} \sum_i Q_i^2 + \frac{1}{2} \frac{(\sum_i \langle \alpha\bar{\beta} \rangle_i Q_i)^2}{\sum_i (\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2)} \end{cases}$$

We therefore have:

$$PC_{inter} \leq PC_{intra}$$

In words, enabling broader trading (weakly) decreases total private production costs.

Proof. We derive the expressions for PC_{intra} and PC_{inter} in Appendix K. We then have:

$$\begin{aligned} (\sum_i \langle \alpha\bar{\beta} \rangle_i Q_i)^2 &= \left(\sum_i \sqrt{\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2} \left(\frac{\langle \alpha\bar{\beta} \rangle_i Q_i}{\sqrt{\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2}} \right) \right)^2 \\ &\leq \left(\sum_i (\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2) \right) \left(\sum_i \frac{(\sum_i \langle \alpha\bar{\beta} \rangle_i Q_i)^2}{\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2} \right) \end{aligned}$$

where the second row is derived from Cauchy-Schwartz inequality. Therefore:

$$\frac{(\sum_i \langle \alpha\bar{\beta} \rangle_i Q_i)^2}{\sum_i (\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2)} \leq \sum_i \frac{(\langle \alpha\bar{\beta} \rangle_i Q_i)^2}{\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2}$$

and thus:

$$PC_{inter} \leq PC_{intra}$$

□

Proposition 1 corresponds to the standard economic intuition that enabling broader allowance trading decreases private compliance costs.

3.3.2 Emissions

We now turn to total emissions. In order to simplify the interpretation of our results, we define for a given sector i :

$$\sigma_i^2 \equiv \frac{1}{N_i} \sum_{s \in i} \sum_{j \in s} (\beta_j - \bar{\beta}_i)^2$$

the variance of firm-level emission intensities (before any abatement) and:

$$\tilde{\sigma}_{\bar{\beta}\hat{\beta},i} \equiv \langle \bar{\beta}\hat{\beta} \rangle_i - \langle \bar{\beta} \rangle_i \langle \hat{\beta} \rangle_i$$

the covariance, within sector i , between subsectors' average emission intensities and their assigned benchmarks.

We further introduce the following notation:

$$\text{Cov}_i(X, Y) \equiv \frac{1}{I} \sum_i X_i Y_i - \left(\frac{1}{I} \sum_i X_i \right) \left(\frac{1}{I} \sum_i Y_i \right)$$

where I is the number of sectors in the economy and (X_i, Y_i) are two variables defined at the sector level. We then get the following result.

Proposition 2 (Ambiguous impact of broader trading on emissions). *Total emissions under intra-sectoral and inter-sectoral trading are equal to:*

$$\left\{ \begin{array}{l} E_{intra} = \sum_i \bar{\beta}_i Q_i - \sum_i \left[\left(\sigma_i^2 + \mu_i Q_i - \tilde{\sigma}_{\bar{\beta}\hat{\beta},i} \right) \frac{\langle \alpha \bar{\beta} \rangle_i Q_i}{\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2} \right] \\ E_{inter} = \sum_i \bar{\beta}_i Q_i - \left(\sum_i \left(\sigma_i^2 + \mu_i Q_i - \tilde{\sigma}_{\bar{\beta}\hat{\beta},i} \right) \right) \left(\frac{\sum_i \langle \alpha \bar{\beta} \rangle_i Q_i}{\sum_i (\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2)} \right) \end{array} \right.$$

Under the simplifying assumption that:

$$\forall i, i', \langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2 = \langle \sigma^2 \rangle_{i'} + \mu_{i'} Q_{i'} + \Omega_{i'}^2$$

moving from intra-sectoral trading to inter-sectoral trading has an ambiguous impact on emissions. Economy-wide emissions decrease if, and only if:

$$\text{Cov}_i \left(\langle \alpha \bar{\beta} \rangle Q, \sigma^2 + \mu Q - \tilde{\sigma}_{\bar{\beta} \hat{\beta}} \right) < 0$$

Proof. We derive the expressions for E_{intra} and E_{inter} in Appendix K.

Under the subsequent simplifying assumption, we have:

$$\forall i, i', \langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2 = \langle \sigma^2 \rangle_{i'} + \mu_{i'} Q_{i'} + \Omega_{i'}^2 \equiv K$$

which implies:

$$E_{inter} - E_{intra} = \frac{I}{K} \times \text{Cov}_i \left(\langle \alpha \bar{\beta} \rangle Q, \sigma^2 + \mu Q - \tilde{\sigma}_{\bar{\beta} \hat{\beta}} \right)$$

Therefore, $E_{inter} < E_{intra}$ if, and only if:

$$\text{Cov}_i \left(\langle \alpha \bar{\beta} \rangle Q, \sigma^2 + \mu Q - \tilde{\sigma}_{\bar{\beta} \hat{\beta}} \right) < 0$$

□

In order to interpret Proposition 2, let's first consider a single sector i where a TPS has been implemented. The absolute change ΔE_i in the total emissions of this sector (relative to their status quo level $\bar{\beta}_i Q_i$) after the implementation of the TPS is:

$$\Delta E_i = - \left(\sigma_i^2 + \mu_i Q_i - \tilde{\sigma}_{\bar{\beta} \hat{\beta}, i} \right) \frac{\langle \alpha \bar{\beta} \rangle_i Q_i}{\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2}$$

In particular, this change in emissions is proportional to:

$$\sigma_i^2 + \mu_i Q_i - \tilde{\sigma}_{\bar{\beta} \hat{\beta}, i}$$

Therefore, the total emissions of the sector decrease (relative to status quo) if, and only if:

$$\sigma_i^2 + \mu_i Q_i > \tilde{\sigma}_{\bar{\beta} \hat{\beta}, i}$$

The left-hand side of the inequality captures how easy it is to decrease emissions in sector i . Specifically, reducing carbon emissions will be easier if (i) firms' emission intensities are heterogeneous (high σ_i^2); or (ii) abatement technologies are cheap (high μ_i). The right-hand side is the covariance (across subsectors) between initial subsector average carbon intensities $\bar{\beta}_s$ and subsector benchmarks $\hat{\beta}_s$. When this covariance is positive, that is, when benchmarks tend to be more lenient in subsectors with high carbon intensities, then total emissions can *increase* relative to the laissez-faire outcome. Such a situation would only arise when decreasing carbon emissions is particularly difficult for that sector (low values of σ_i^2 and μ_i).

Overall, the expression $\sigma_i^2 + \mu_i Q_i - \tilde{\sigma}_{\bar{\beta}\hat{\beta},i}$ can be thought of as a measure of the ability of a TPS to decrease emissions in sector i . Implementing a TPS in a single sector will reduce emissions more when firms have more heterogeneous emission intensities, cheaper abatement opportunities and when benchmarks are relatively more stringent for the more polluting sub-sectors.

With this intuition in mind, we now go back to the case of multiple sectors. Proposition 2 shows that, under a simplifying assumption, whether broader trading decreases emissions depends on the covariance across sectors between two quantities: $\langle \alpha\bar{\beta} \rangle_i Q_i$ on the one hand, and $\sigma_i^2 + \mu_i Q_i - \tilde{\sigma}_{\bar{\beta}\hat{\beta},i}$ on the other hand. The first quantity ($\langle \alpha\bar{\beta} \rangle_i Q_i$) captures the magnitude of the emission reduction “burden” placed on sector i . The second quantity ($\sigma_i^2 + \mu_i Q_i - \tilde{\sigma}_{\bar{\beta}\hat{\beta},i}$) has been discussed above and captures the ability of a TPS to decrease emissions in sector i .

Therefore, broader allowance trading decreases emissions when sectors with a higher “burden” in terms of targeted emission reductions are also the ones where decreasing emissions is more “difficult”. Intuitively, when the largest emission reductions are targeted in sectors where a standalone TPS is not very effective, then intra-sectoral trading achieves very limited emission reductions. Broader allowance trading in turn enables to tap into sectors where higher emission reductions are achievable. Note however that, if benchmarks are uniform within each sector, then $E_{intra} = E_{inter}$ (see Section 3.4 below). Therefore, having heterogeneous subsector benchmarks is a necessary condition for total emissions to vary with the scope of allowance trading (given our inelastic demand assumption). In other words, the mechanism underlying the change in emissions relates to the heterogeneity in the implicit output subsidies within each sector, which generates distortions that may be either exacerbated or reduced when broader allowance trading is introduced.

Finally, given the ambiguous impact of broader trading on emissions, it is tempting to speculate about which outcome is most likely to occur in practice. One such speculation is that political acceptability considerations may limit the amount of emission reductions that can be asked from subsectors for which decarbonization is very challenging. If so, increasing allowance trading scope may be more likely to increase emissions.

3.3.3 Social welfare

We now combine the results on private costs and emissions to discuss how broader allowance trading impacts welfare.

Proposition 3 (Broader trading and welfare). *Moving from intra-sectoral to inter-sectoral allowance trading:*

- *is welfare-improving if emissions decrease.*
- *has an ambiguous impact on welfare if emissions increase. More specifically, there exists a threshold value \hat{t} such that welfare increases if, and only if:*

$$t^* < \hat{t}$$

where t^* is the social cost of carbon.

Proof. As discussed above, the change ΔSW in social welfare is:

$$\Delta SW = -\Delta SC = -\Delta PC - \Delta E t^*$$

By Proposition 1, $-\Delta PC \geq 0$. Therefore, if $\Delta E \leq 0$, then $\Delta SW \geq 0$. If however emissions increase when moving from intra-sectoral to inter-sectoral trading, then $\Delta SW \geq 0$ if, and only if:

$$t^* \leq \frac{-\Delta PC}{\Delta E} \equiv \hat{t}$$

□

In words, Proposition 3 simply states that, if emissions increase, then there exist a threshold SCC beyond which the environmental cost of higher emissions outweighs the private gains derived from broader allowance trading. Whether the corresponding threshold SCC is low enough to be of practical relevance is an empirical question, which we tackle in Section 4.

3.4 Intensity benchmark setting

An important decision of policymakers implementing a TPS is setting the values of intensity benchmarks. This section highlights the key role played by heterogeneous within-sector benchmarks on the impacts of broader trading on emissions and welfare. We first discuss the special case of uniform within-sector benchmarks and then turn to optimal benchmark setting.

3.4.1 Uniform within-sector benchmarks

Consider the situation where each sector faces a single benchmark $\hat{\beta}_i$. In other words, we assume that:

$$\forall s \in i, \hat{\beta}_s = \hat{\beta}_i = (1 - \alpha_i)\bar{\beta}_i$$

Aggregate emissions are then:

$$E = \sum_i \sum_{s \in i} \sum_{j \in s} \hat{\beta}_i q_j = \sum_i \hat{\beta}_i \sum_{s \in i} \sum_{j \in s} q_j = \sum_i \hat{\beta}_i Q_i \quad (13)$$

where the second equality uses the fact that benchmarks are uniform within a sector, and the last equality the assumption that sector-level demands are inelastic. Hence, similarly to what happens under C&T, aggregate emissions do not depend on the scope of allowance trading when sectors have uniform within-sector benchmarks. Because broader trading weakly decreases private compliance costs (Proposition 1), it is thus weakly welfare improving.

Corollary 1 (Uniform within-sector benchmarks). *When benchmarks are uniform within each sector, expanding the scope of allowance trading (weakly) improves welfare.*

3.4.2 Optimal benchmark setting

Finally, we turn to the question of optimal benchmark setting. We start with the simple case of a single-sector TPS and thus drop the index i . We then return to the multi-sector TPS case.

Proposition 4 (Socially efficient benchmarks for a single sector). *For a single sector under TPS, it is socially optimal to implement a uniform benchmark $\hat{\beta}^*$ across subsectors. Optimal subsector benchmarks are then such that:*

$$\forall s, \hat{\beta}_s = \hat{\beta}^* = \bar{\beta} - (\sigma^2 + \mu Q) \frac{t^*}{Q}$$

The corresponding minimal social cost that a TPS can achieve is:

$$SC_{TPS}^* = \frac{1}{2}Q^2 + \bar{\beta}Q - \frac{1}{2}(\sigma^2 + \mu Q)(t^*)^2$$

Proof. See Appendix K. □

Importantly, given our simplifying assumptions,¹⁶ optimally-designed benchmarks achieve the first-best outcome for a single sector under TPS.

Returning to the multiple-sector case, if socially-optimal uniform benchmarks are implemented in each sector, then intra-sectoral trading achieves the first-best outcome. Therefore, there is no welfare gain to be reaped if uniform benchmarks were set optimally in each sector.

However, the fact that heterogeneous within-sector benchmarks are implemented in practice, along with the choice of a TPS over a C&T, suggests that aggregate social welfare is unlikely to be the sole objective of the government. While we show in Appendix D that heterogeneous within-sector benchmarks might be rationalized by political acceptability constraints, we leave a more in-depth investigation of political economy constraints for further research.

3.5 Discussion

Our analytical model provides useful insights on why and when expanding the scope of allowance trading may decrease social welfare under a TPS. Table 1 summarizes our main analytical predictions, which we test in the next section.

Table 1: Summary of analytical results

Case	Production costs	Emissions	Social Welfare
Heterogeneous within-sector benchmarks	$PC_{inter} \leq PC_{intra}$	$E_{inter} \lesseqgtr E_{intra}$	$E_{inter} > E_{intra}$ is likely for political acceptability reasons. Welfare ranking then depends on the social cost of carbon
Uniform within-sector benchmarks	$PC_{inter} \leq PC_{intra}$	$E_{inter} = E_{intra}$	Intersectoral trading is unambiguously welfare improving

The main takeaway is that setting intensity benchmarks that differ across subsectors creates another source of inefficiency on top of the distortions induced by output subsidies. This observation has important policy implications for the next phases of the Chinese TPS and beyond. First, when politically feasible, uniform benchmarks should be implemented.

¹⁶In particular, this result would not hold in a more general setting with an elastic demand (see [Goulder et al. \(2022\)](#)).

Second, if heterogeneous within-sector benchmarks are to be maintained, additional policy tools may be considered to mitigate their (possibly) detrimental impact. One such tool could be trading ratios, which have been discussed in related settings (Bento et al., 2015; Woerman, 2023). Indeed, let us assume that policy parameters are such that broader trading decreases welfare. We denote with t_i the equilibrium allowance price in sector i in the intra-sectoral trading scenario. Let us further assume that the scope of trading is expanded with the additional constraint that one allowance in sector i is worth t_i/t_1 “fungible” allowances. Then, the effective allowance price faced by firms in sector i is t_i , which induces them to make the same decisions as in the intra-sectoral trading scenarios. Therefore, there exist trading ratios that can ensure that broader trading (weakly) increases welfare relative to intra-sectoral trading.

In order to keep our model tractable, we have relied on a number of simplifying assumptions. First, we have assumed that the demand for the good produced in each sector is inelastic. As discussed in Appendix A, allowing demand to be elastic would strengthen our main finding that broader trading does not necessarily increase welfare. Indeed, with elastic demands, inter-sectoral trading may increase emissions relative to intra-sectoral trading even when benchmarks are uniform within each sector. In the numerical simulations below, we discuss how introducing demand elasticity changes the obtained results. Second, we have assumed for tractability that abatement opportunities enter the cost function uniformly within a sector. We discuss heterogeneous abatement costs in Appendix B. The numerical model allows for more heterogeneity in terms of abatement possibilities and performs sensitivity analyses. Third, we assumed product markets to be perfectly competitive. Appendix C shows how one may account for market power within our analytical framework in a tractable way. Fourth, we assumed away the possibility that some firms may shut down because of the TPS. This assumption is relaxed in our numerical simulations. Finally, we have assumed that benchmarks can be arbitrarily given. In practice, these benchmarks are likely to result from various political acceptability constraints. In particular, we show in Appendix D that heterogeneous within-sector benchmarks may be rationalized by acceptability constraints. Similarly, the choice of intra- versus inter-sectoral trading is likely to be influenced by political economy considerations. However, a deeper dive into political economy considerations when designing a TPS is beyond the scope of this paper.

Because trying to relax all these assumptions at the same time would prove intractable, we instead run a realistic numerical application calibrated to China’s TPS in Section 4.

4 Numerical simulations

Our analytical model demonstrates that expanding the scope of allowance trading under a TPS may reduce welfare, contrary to standard economic intuition. However, the practical relevance of this counter-intuitive theoretical finding needs to be tested empirically for at least a couple of reasons. First, the values of key parameters, such as benchmarks and the social cost of carbon, may imply that this issue does not arise in practice. Second, the magnitude of the implied inefficiencies might prove to be negligible. To address these concerns, this section runs a numerical application tailored to China’s TPS.

4.1 Numerical model

We employ a dynamic general equilibrium model originally developed by [Goulder et al. \(2023\)](#). We assess the equilibrium reached by China’s TPS under different scenarios. The model is uniquely suitable for assessing the impacts of China’s TPS as it carefully considers the design of TPS and its associated impacts. It distinguishes itself from earlier models in two main aspects.

First, the model encompasses the entire economy by dividing production into 31 sectors with detailed sector disaggregation and plant-level data (Table 2). This enables us to account for heterogeneity in emission intensities, abatement costs, and the design of heterogeneous within-sector benchmarks. Specifically, the model includes detailed sector disaggregations for the sectors whose emissions will be covered in the initial two phases of China’s TPS (see Appendix E). In particular, the electricity sector is disaggregated into 15 subsectors relying on different technologies. Among these subsectors, the first 11 are fossil-fueled but differ in terms of fuel input (coal or gas), plant capacity, and temperature & pressure specifications (subcritical, supercritical, etc.) and the remaining 4 subsectors are low-carbon electricity, including wind, solar, nuclear and hydro.¹⁷ The aluminum and cement sectors have three subsectors each, which differ in terms of emission intensities. The iron & steel sector has two technology categories,¹⁸ and each category is further divided into three subsectors based on

¹⁷Using plant-level data, the electricity sector is divided into 15 subsectors: 1000MW Ultra-supercritical; 600MW Ultra-supercritical; 600MW Supercritical; 300MW Supercritical; 600MW Subcritical; 300MW Subcritical; Installed capacity less than 300MW; Circulating Fluidized Bed Units with installed capacity greater than or equal to 300MW; Circulating Fluidized Bed Units with installed capacities less than 300MW; Gas fired plants, F-class; Gas fired plants, Pressure lower than F-class; Wind power; Solar power; Hydropower; and Nuclear power.

¹⁸The two categories are basic oxygen steelmaking and electric arc furnace steelmaking.

their emission intensities.

Second, the model is dynamic and spans from 2020 to 2030 in order to encompass the next implementation phases of China’s TPS as well as the ongoing and planned reforms. The model incorporates institutional and regulatory features of China’s economy, which include the ongoing market reform efforts taking place in the electricity sector, the preferential treatment of state-owned enterprises and all pre-existing energy policies. It also accounts for structural shifts within China’s economy. By considering these factors, our model provides a comprehensive analysis of the complex dynamics and evolving landscape of China’s economy in the context of the TPS. Further details about the model, data and parameters can be found in [Goulder et al. \(2023\)](#).

Table 2: Sectors covered by the multi-sector general equilibrium model

Short name	Description	Added to TPS
Agriculture	Crop cultivation, forestry, livestock and fishery	No
Aluminum	Aluminum products	Phase 2
Cement	Cement	Phase 2
Clothing	Clothing	No
Coal	Coal mining and processing	No
Construction	Construction	No
Crude oil	Extraction of crude oil	No
Daily chemical products	Chemical fibers, medicines, rubber and plastics products	No
Electricity	Electricity	Phase 1
Electronic equipment	Electronic equipment manufacturing	No
Food	Food and tobacco	No
Gas distribution	Gas distribution	No
General equipment	General equipment manufacturing	No
Heat	Heat	No
Iron & steel	Iron and steel	Phase 2
Log furniture	Log and furniture	No
Metal products	Metal products	No
Mining	Metal minerals mining and non-metal minerals	No
Natural gas	Extraction of natural gas	No
Oil refinery	Petroleum refining, coking and nuclear fuels	Phase 3
Other manufacturing	Other manufacturing	No
Other non-ferrous	Non-ferrous metals other than aluminum	Phase 3
Other non-metal	Non-metal processing other than cement	Phase 3
Paper & pulp	Paper and pulp	Phase 3
Printing and stationery	Printing and stationery	No
Raw chemicals	Raw chemical materials, chemical products	Phase 3
Services	Services	No
Textile	Textile	No
Transport	Transport and post	No
Transport equipment	Transport equipment manufacturing	No
Water	Water	No

We examine the impacts of the TPS over its three planned phases. As noted in Section 2, the TPS starts in 2020 and covers only the electricity sector in Phase 1. Phase 2 begins in late 2023 and expands the sectoral coverage to cement, aluminum and iron&steel. It is then followed by Phase 3, which is planned to start in 2026 and will add more manufacturing sectors.

In our central-case simulations, we consider scenarios with inter-sectoral and intra-sectoral allowance trading while applying heterogeneous within-sector benchmarks. For the electricity sector, we impose four benchmarks consistent with China’s TPS design: three specifically designed for coal-fired generators and one for gas-fired generators.¹⁹ In the iron & steel sector, two benchmarks are applied, corresponding to the basic oxygen process and the electric arc furnace process. All other sectors are assumed to face uniform sector-level benchmarks. We then conduct sensitivity analysis to consider uniform within-sector benchmarks.

The initial benchmarks for the electricity sector in 2020 and 2021 are the actual benchmarks set by the Ministry of Ecology and Environment. In sectors where benchmarks have not been officially announced, we assume that the first-year benchmark for each newly-added sector in Phases 2 and 3 is set at 2.5% below their output-weighted average baseline emission intensity from the year preceding their inclusion in the TPS. Regarding the rate at which stringency tightens, the benchmarks for the electricity sector decrease by 0.5% annually during Phase 1, following the guidelines of the Ministry of Ecology and Environment. In Phases 2 and 3, these benchmarks are assumed to decline by 1%. For other sectors, the benchmarks decline by 2.5% annually. Detailed benchmark values are reported in Appendix F.

4.2 Main results

We first present the results of the inter-sectoral and intra-sectoral allowance trading with heterogeneous within-sector benchmarks. Table 3 shows the private costs and economy-wide emission reductions. Since only one sector is covered in Phase 1, distinctions between inter-sectoral and intra-sectoral scenarios emerge only from Phase 2 onward. In the case of inter-sectoral trading, the overall present value cost to the economy for the period of 2020-2030, measured with an annual discount rate of 5%,²⁰ amounts to approximately \$82 billion

¹⁹The coal-fired generators have three distinct benchmarks: one for coal-fired generators with capacity ≤ 300 MW, one for coal-fired generators with capacity > 300 MW, and one for circulating fluidized-bed generators.

²⁰This discount rate reflects the average capital growth rate in China.

USD. In contrast, the overall cost under intra-sectoral trading reaches about \$117 billion. The inter-sectoral trading case thus exhibits a 30% lower private cost compared to intra-sectoral trading. Expanding allowance trading scope indeed redirects abatement efforts to the facilities that can reduce emissions at the lowest (private) costs, thereby lowering overall compliance costs. This finding aligns with Proposition 1. Furthermore, the difference in private cost between the two cases increases over time. The difference is only 24% during Phase 2, but subsequently increases to 31% in Phase 3. This indicates that both the higher stringency level resulting from tightening benchmarks and the inclusion of more sectors into the TPS contribute to greater economic benefits derived from trading.

Table 3: Private costs and emission reductions under inter-sectoral and intra-sectoral trading

year	Private cost (billion 2020\$)		Emission reduction (million ton)	
	Inter-sectoral	Intra-sectoral	Inter-sectoral	Intra-sectoral
2020	0.70	0.70	120	120
2021	0.82	0.82	137	137
2022	0.92	0.92	152	152
2023	1.46	2.03	278	304
2024	2.88	3.78	438	468
2025	4.79	6.21	608	640
2026	6.62	9.59	814	858
2027	9.73	13.95	1038	1085
2028	13.50	19.38	1272	1318
2029	17.95	26.04	1516	1561
2030	23.03	34.01	1767	1809
Total	82.41	117.44	8141	8455
Difference	35.03		313	

Nevertheless, as shown in Table 3, inter-sectoral trading results in smaller emission reductions compared to intra-sectoral trading. Over the period 2020-2030, the inter-sectoral trading case achieves a cumulative CO₂ emission reduction of 8,141 million tons, lower than the 8,455 million ton reduction achieved under the intra-sectoral trading case. This finding suggests that the sectors with higher emission reduction targets may not be the ones facing the greatest challenges in reducing emissions. To provide further evidence, we compute the covariance between sectoral emission reductions and sectoral allowance prices. The sectoral allowance price serves as a proxy for the sectoral marginal abatement cost, reflecting the difficulty of reducing emissions. This covariance is negative in nearly all years, which aligns

with the predictions of Proposition 2. The plots of sectoral allowance prices and sectoral cumulative emission reductions are reported in Appendix G.

Since inter-sectoral trading induces higher total emissions than intra-sectoral trading, we next assess the corresponding environmental cost resulting from increased emissions. To determine the threshold SCC at which the environmental cost exceeds private economic gains from broader trading, we evaluate the implied changes in social welfare for different SCC values. Our findings reveal that broader trading yields higher social welfare when the SCC is relatively small. However, as soon as the SCC exceeds \$91/ton,²¹ narrower trading becomes welfare-improving, and the difference in social welfare between the two scenarios widens as the SCC increases further (Proposition 3). To contextualize this threshold, we can compare it to existing SCC estimates found in the literature. For example, Nordhaus (2017) estimates the SCC to be around \$44/ton, and the Biden administration (2021) estimates it to be approximately \$51/ton. In contrast, a recent comprehensive study on SCC provides an estimate of \$185/ton (Rennert et al., 2022), which largely exceeds our threshold.

In addition to the total welfare change, another important policy consideration is the distributional impacts across sectors. Appendix H presents the cumulative changes in output prices and production levels broken down by sector. In both the inter-sectoral and intra-sectoral trading cases, most sectors experience price increases due to the increase in production costs resulting from the TPS policy. However, all Phase 2 sectors except the iron & steel sector, which are electricity, cement and aluminum sectors, exhibit significantly higher output prices and lower production levels in the intra-sectoral trading case compared to the inter-sectoral trading case. This disparity is likely to be attributable to the higher marginal abatement costs faced by these sectors.²² Consequently, expanding trading scope is likely to enhance the political acceptability of the TPS, despite its potentially detrimental impact on social welfare.

²¹As noted above, the SCC is in 2020 value and is assumed to increase by 3% annually.

²²The aluminum sector has high abatement costs primarily because it heavily relies on electricity as an input. The cement sector faces the second-highest allowance price, mainly due to the difficulty of reducing emissions resulting from its production processes.

4.3 Sensitivity analyses

4.3.1 Within-sector benchmark heterogeneity

Corollary 1 highlights that the within-sector heterogeneity in benchmarks plays an important role in the comparison between intra-sectoral and inter-sectoral allowance trading. Specifically, smaller heterogeneity in benchmarks tends to increase the likelihood that broader trading will improve welfare. To assess the influence of this heterogeneity, we conduct simulations for a situation where a uniform benchmark is imposed in the electricity sector. In this scenario, all subsectors within the electricity sector are assigned the same benchmark value, which is the output-weighted average benchmark of the four benchmarks used in the central case. This assumption is meant to ensure that the overall stringency remains unchanged.

Appendix I shows the private costs and emission reductions under this uniform within-sector benchmark case. In the uniform-benchmark case, broader trading results in greater percentage reductions in private costs compared to the heterogeneous-benchmark case. This occurs because broader trading brings the marginal abatement costs closer to being equal, thus benefiting the uniform-benchmark case more. Furthermore, broader trading leads to a smaller increase in emissions under the uniform-benchmark case compared to the heterogeneous-benchmark case. Consequently, the smaller the variation in benchmarks, the more likely broader trading is to improve welfare. Consistently, the SCC threshold for the uniform-benchmark case is \$114/ton, and is thus higher than the threshold of \$91/ton obtained in the heterogeneous-benchmark case.

We further explore optimal benchmark setting, building on Proposition 4. This proposition suggests that, for a single-sector TPS, a uniform benchmark can be socially efficient. To evaluate the impacts of different sets of benchmarks on social welfare, we examine four cases. The first case corresponds to the uniform within-sector benchmark scenario discussed above. The second case imposes two benchmarks for electricity generators, one for coal-fired generators and the other for gas-fired generators. The third case corresponds to the central case where four benchmarks are used in the electricity sector. The fourth case imposes 11 different benchmarks for the 11 fossil electricity subsectors. Appendix I compares the obtained results for these four cases. Overall, the cost per ton of reduced emission increases with heterogeneity in benchmarks: the uniform-benchmark case achieves the lowest cost per ton of reduced emission.

4.3.2 Demand elasticity

An important simplifying assumption of our analytical model is that sector-level demands are inelastic. This assumption is relaxed in the central case. This sensitivity analysis explores the role of demand elasticity. Appendix J presents the economy-wide emission reduction in the uniform-benchmark case, with elastic and inelastic demands, respectively. Consistently with our analytical prediction, under inelastic demand, the difference in emission reductions between inter-sectoral and intra-sectoral trading is negligible, and the difference in private costs is larger, compared to the results under elastic demand. Consequently, sectors facing more inelastic demand would benefit more from inter-sectoral trading. These sectors would indeed need to rely more on reducing emissions intensities (rather than reducing output) in the intra-sectoral trading case, which leads to higher abatement costs.

Importantly, with inelastic demand and uniform within-sector benchmark, broader trading is unambiguously welfare-improving, because emission reductions are nearly identical and private costs are lower in the inter-sectoral trading case. These results validate the findings of Corollary 1 and underscore the benefits of broader trading in sectors with more inelastic demand.

4.3.3 Abatement cost

The impact of expanding trading scope also depends on the ease of reducing emissions, which closely relates to the ability to decrease emission intensity. To examine this aspect, we modify the elasticity of substitution between the fuel composite input and the factor (labor and capital) composite input in our numerical model. A higher elasticity indicates greater ease in reducing emission, as emission reductions can rely less on output reduction and more on input substitution.

Appendix J illustrates how the quantitative results change with varying abatement costs. We observe lower abatement costs tend to reduce the differences in private costs between inter-sectoral and intra-sectoral trading, because firms now find it easier to reduce emissions in the intra-sectoral trading case than under the central-case abatement costs. Low abatement cost case thus has a lower SCC threshold than the central case. While the exact magnitudes may vary, the overall patterns and conclusions hold across different levels of ease in reducing emission intensity.

5 Conclusion

Under a tradable performance standards (TPS), firms receive an amount of free allowances equal to their assigned benchmark multiplied by the quantity of goods they produce. The total number of allowances is hence endogenous to firms' output decisions, and changing the breadth of allowance trading can impact total emissions.

This paper examines the conditions under which expanding the scope of allowance trading in a TPS is welfare improving. We find that this expansion may result in higher emissions when the sectors with larger targeted emission reductions are the ones facing smaller challenges in reducing them. In other words, broader trading may end up increasing total emissions, and can thus – somewhat counter-intuitively – decrease welfare relative to narrower trading.

Using a dynamic general equilibrium model, we conduct a numerical analysis to evaluate the cost-effectiveness and distributional impacts of China's TPS over the period 2020-2030 under different trading scopes. First, we find that, if the SCC exceeds \$91/ton, inter-sectoral trading achieves lower social welfare compared to intra-sectoral trading. Second, we run several sensitivity analyses to discuss underlying mechanisms. In particular, we study a scenario where the electricity sector is subject to a uniform benchmark, instead of four subsector-specific benchmarks. We find broader trading to be more likely to increase welfare under such a scenario.

These findings highlight that heterogeneous within-sector benchmarks can be an important shortcoming of a TPS, beyond the already documented lower efficiency of a TPS compared to a C&T due to implicit output subsidies. More generally, the observation that expanding trading scope has an ambiguous impact on aggregate emissions under a TPS represents another advantage of transitioning towards a C&T system. Indeed, a broader trading scope is unambiguously welfare improving under a C&T system, where the allocation of allowances is exogenous and not influenced by firms' production decisions.

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Appendix

A Elastic demand

This Appendix extends our analytical framework to allow for an elastic sector-level demand. Specifically, we assume that the demand function $D_i(p)$ in sector i is linear and equal to:

$$D_i(p) \equiv Q_i - b_i p$$

In order to be able to derive closed-form expressions, we assume that it is not possible to abate emissions through investments that reduce the carbon intensity of production (i.e. $\mu_i = 0$ for all i).

Let t_i denote the emission allowance price in sector i and p_i the output price, firm $j \in s$ solves:

$$\max_{q,a} p_i q - \frac{1}{2} N_i q^2 - (\beta_j - \hat{\beta}_s) q t_i$$

so that:

$$q_j = \frac{1}{N_i} [p_i - (\beta_j - \bar{\beta}_s) t_i - \alpha_s \bar{\beta}_s t_i] \quad (\text{A.1})$$

The market clearing condition in the product market is:

$$\sum_{s \in i} \sum_{j \in s} q_j = D_i(p_i) = Q_i - b_i p_i \quad (\text{A.2})$$

which gives:

$$p_i = \frac{1}{1 + b_i} [Q_i + \langle \alpha \bar{\beta} \rangle_i t_i] \quad (\text{A.3})$$

Finally, equilibrium allowance prices are given by the market-clearing condition in the allowance market(s) (see Appendix K):

- In the intra-sectoral trading case:

$$t_i = \frac{\frac{1}{1+b_i} \langle \alpha \bar{\beta} \rangle_i Q_i}{\langle \sigma^2 \rangle_i + \Omega_i^2 + \frac{b_i}{1+b_i} \langle \alpha \bar{\beta} \rangle_i} \quad (\text{A.4})$$

- In the inter-sectoral trading case:

$$t = \frac{\sum_i \frac{1}{1+b_i} \langle \alpha \bar{\beta} \rangle_i Q_i}{\sum_i \left(\langle \sigma^2 \rangle_i + \Omega_i^2 + \frac{b_i}{1+b_i} \langle \alpha \bar{\beta} \rangle_i \right)} \quad (\text{A.5})$$

Note in particular that if we denote:

$$\lambda_i \equiv \langle \sigma^2 \rangle_i + \Omega_i^2 + \frac{b_i}{1+b_i} \langle \alpha \bar{\beta} \rangle_i > 0 \quad (\text{A.6})$$

we have:

$$t = \frac{\sum_i \lambda_i t_i}{\sum_i \lambda_i} \quad (\text{A.7})$$

In order to compare both scenarios, we go back to Equation 7 and use social surplus as our welfare metric:

$$SW = GCS - PC - EC$$

Expressing the different terms as a function of the allowance price t_i (which may or may not be uniform across sectors depending on the considered scenario), we get that:

- Gross consumer surplus GCS_i in sector i is equal to:

$$GCS_i = \frac{Q_i^2}{2b_i} - \frac{b_i}{2(1+b_i)^2} (Q_i + \langle \alpha \bar{\beta} \rangle_i t_i)^2 \quad (\text{A.8})$$

- Total private productions costs PC_i in sector i are equal to:

$$PC_i = \frac{1}{2} \left(Q_i - \frac{b_i}{1+b_i} \langle \alpha \bar{\beta} \rangle_i t_i \right)^2 + \frac{1}{2} (\langle \sigma^2 \rangle_i + \Omega_i^2) t_i^2 \quad (\text{A.9})$$

- Total emissions E_i from sector i are equal to:

$$E_i = \frac{1}{1+b_i} \bar{\beta}_i Q_i - \left[\sigma_i^2 - \tilde{\sigma}_{i,\bar{\beta}\hat{\beta}} + \frac{b_i}{1+b_i} \bar{\beta}_i \langle \alpha \bar{\beta} \rangle_i \right] t_i \quad (\text{A.10})$$

As a first-order Taylor approximation in b_i , we have:

$$\lambda_i \simeq \langle \sigma^2 \rangle_i + \Omega_i^2 + b_i \langle \alpha \bar{\beta} \rangle_i \quad (\text{A.11})$$

and:

$$(GCS_i^{inter} - PC_i^{inter}) - (GCS_i^{intra} - PC_i^{intra}) = \frac{1}{2} \lambda_i (t_i^2 - t^2) \quad (\text{A.12})$$

Summing this expression across sectors and recalling Equation A.7, we get from Cauchy-Schwartz inequality that:

$$(GCS_i^{inter} - PC_i^{inter}) \geq (GCS_i^{intra} - PC_i^{intra}) \quad (\text{A.13})$$

Therefore, in order to be potentially welfare-improving relative to the inter-sectoral trading case, the intra-sectoral trading scenario must induce lower aggregate emissions. This necessary condition is:

$$\sum_i E_i^{inter} > \sum_i E_i^{intra} \quad (\text{A.14})$$

that is:

$$\sum_i \left[\sigma_i^2 - \tilde{\sigma}_{i,\bar{\beta}\bar{\beta}} + \frac{b_i}{1+b_i} \bar{\beta}_i \langle \alpha \bar{\beta} \rangle_i \right] (t_i - t) > 0 \quad (\text{A.15})$$

Under the simplifying assumption that:

$$\langle \sigma^2 \rangle_i + \Omega_i^2 + \frac{b_i}{1+b_i} \langle \alpha \bar{\beta} \rangle_i = \langle \sigma^2 \rangle_{i'} + \Omega_{i'}^2 + \frac{b_{i'}}{1+b_{i'}} \langle \alpha \bar{\beta} \rangle_{i'} \text{ for all } i, i'$$

this condition may be rewritten:

$$\mathbf{Cov}_i \left(\frac{1}{1+b} \langle \alpha \bar{\beta} \rangle Q, \sigma^2 - \tilde{\sigma}_{\bar{\beta}\bar{\beta}} + \frac{b}{1+b} \bar{\beta} \langle \alpha \bar{\beta} \rangle \right) > 0 \quad (\text{A.16})$$

This expression has a similar flavor as its simplified version for inelastic demand reported in the main text. However, it is no longer the case that emissions are identical under intra- and inter-sectoral trading when intensity benchmarks are uniform within each sector.

B Within-sector heterogeneity in abatement costs

In this Appendix, we consider a given sector where firms have a uniform initial carbon intensity β . Firms are however heterogeneous in their abatement cost parameter μ_j . Under a single benchmark TPS mechanism, each firm j solves:

$$\max_{a,q} pq - \frac{1}{2} \left[Nq^2 + \frac{q}{\mu_j} a^2 \right] - (\beta - a - \hat{\beta})qt \quad (\text{B.1})$$

Using the set of first-order conditions and the market clearing condition in the output market we get:

$$a_j(t) = \mu_j t \text{ and } q_j(t) = \frac{1}{N} \left[Q + \frac{1}{2} (\mu_j - \bar{\mu}) t^2 \right]$$

where:

$$\bar{\mu} \equiv \frac{1}{N} \sum_j \mu_j$$

The market-clearing condition in the allowance mechanism is:

$$\sum_j (\beta - a_j(t) - \hat{\beta}) q_j(t) = 0$$

Inserting the expressions for a_j and q_j yields the following equilibrium condition for t

$$t^3 + \frac{2\bar{\mu}Q}{\sigma^2}t - \frac{2\alpha\beta Q}{\sigma^2} = 0 \quad (\text{B.2})$$

where σ^2 is now the variance in the abatement cost parameter:

$$\sigma^2 \equiv \frac{1}{N} \sum_j (\mu_j - \bar{\mu})^2$$

Equation (B.2) admits a unique real root which can be derived with Cardano's formula:

$$t = \sqrt[3]{\frac{\alpha\beta Q}{\sigma^2}} \left[\sqrt[3]{1 + \sqrt{1 + \frac{8}{27} \frac{\bar{\mu}^3 Q}{(\alpha\beta\sigma)^2}}} + \sqrt[3]{1 - \sqrt{1 + \frac{8}{27} \frac{\bar{\mu}^3 Q}{(\alpha\beta\sigma)^2}}} \right] \quad (\text{B.3})$$

Although closed-form, the formula for the equilibrium tax is much less tractable than the formula for the allowance price under the polar situation with heterogeneous carbon intensities and uniform abatement opportunities we consider in the main text of the paper.

C Imperfect competition

In this Appendix, we study the interaction between carbon pricing and market power. It is a well-known fact in environmental economics that, in the absence of corrective policies, two market failures combined may yield a better outcome than each market failure in isolation. For example, a negative externality implies production levels that are too high in the absence of Pigouvian taxation. However, the exercise of market power in a Cournot setting translates into a contraction of output. As a result, a market with imperfect competition and a negative externality could, by chance, reach the first-best outcome. In contrast, setting a Pigouvian tax at the social marginal cost (without implementing antitrust policy) or restoring perfect competition (without addressing the externality) would only achieve a second-best outcome.

To investigate the interaction between market power and carbon pricing in the context of the TPS, we make a number of simplifying assumptions to keep our model tractable. We introduce these assumptions in the next paragraph. We then discuss the TPS mechanism for the sector-specific benchmark case.

C.1 Notations

In this paragraph, we introduce additional notations and assumptions in order to introduce imperfect competition in our framework. To simplify the exposition, we consider a single sector and drop the index i . We further assume that abatement technologies are not available ($\mu = \infty$).

We assume that a dominant firm, indexed by 0, consists of the merger of n smaller firms (with $1 \leq n < N$). In other words, the sector is composed of a dominant firm and $N - n$ smaller firms that represent a price-taking competitive fringe.²³

We denote $\Phi \equiv \frac{n}{N} \in]0, 1[$. This parameter captures the degree of market power possessed by the dominant firm. The higher Φ , the higher the degree of market power that the dominant firm can exert.

As before, the cost function of a firm j in the competitive fringe ($j \in \{1, \dots, N - n\}$) is:

$$c_j(q) = \frac{1}{2} N q^2$$

Because the dominant firm controls n previously competitive smaller firms (which may for example be thought of as a single plant), we assume that the cost function of the dominant firm is:

$$c_0(q) = \frac{1}{2} \frac{N}{n} q^2 = \frac{1}{2} \frac{q^2}{\Phi}$$

In the same spirit, we maintain the assumption that total demand Q is inelastic. Despite the inelastic aggregate demand, the dominant firm faces a downward sloping residual demand curve, defined as gross demand minus the production of the competitive fringe. Indeed, the production level of the competitive fringe increases with the output price.

As before, firm $j \in \{0, \dots, N - n\}$ emits:

$$e_j = \beta_j q_j$$

We denote:

²³Our model of imperfect competition hence builds on [Perry and Porter \(1985\)](#), restricting attention to a simplified setting.

$$\bar{\beta} \equiv \frac{1}{N} \left[n\beta_0 + \sum_{j=1}^{N-n} \beta_j \right]$$

which corresponds to the average carbon intensity of the sector used in the previous sections.

Finally, we also denote:

$$\sigma^2 \equiv \frac{1}{N} \left[n(\beta_0 - \bar{\beta})^2 + \sum_{j=1}^{N-n} (\beta_j - \bar{\beta})^2 \right]$$

C.2 Laissez-faire and first-best

Before introducing the TPS, it is worth solving a number of benchmark situations to build economic intuition. We thus start by computing the achieved outcomes under four situations:

- **Case 1 - Competitive market with no carbon pricing:** firms behave competitively but do not have to pay anything for their carbon emissions;
- **Case 2 - Competitive market with carbon tax:** a Pigouvian tax t^* is set at the social cost of carbon and firms behave competitively;
- **Case 3 - Market power with no carbon pricing:** the dominant firm exercise market power in the absence of any carbon price;
- **Case 4 - Market power with carbon tax:** Pigouvian tax t^* is set at the social cost of carbon and the dominant firm exerts market power.

For each of these situations, we can derive the main outcomes of interest.

Proposition 5 (Laissez-faire and first-best under imperfect competition). *Table C.1 reports (i) the production level q_0 of the dominant firm; (ii) the production level q_j of a firm belonging to the competitive fringe ($1 \leq j \leq N - n$); and (iii) the volume of total emissions.²⁴*

Proof. For each case, we first derive the output of competitive firms as a function of the output price. We then compute the residual demand curve faced by the dominant firm and solves its profit-maximization problem to determine how much it chooses to produce. \square

²⁴Private costs and overall social costs can also be derived from equilibrium firm outputs but are not reported to avoid overloading the Table.

Table C.1: Main outcomes for laissez-faire and first-best under imperfect competition

	q_0	q_j ($j \geq 1$)	Emissions
Case 1	ΦQ	$\frac{Q}{N}$	$\bar{\beta} Q$
Case 2	$\Phi [Q + (\bar{\beta} - \beta_0)t^*]$	$\frac{1}{N} [Q + (\bar{\beta} - \beta_j)t^*]$	$\bar{\beta} Q - \sigma^2 t^*$
Case 3	$\frac{\Phi}{1 + \Phi} Q$	$\frac{1}{N} \frac{1}{1 - \Phi^2} Q$	$\bar{\beta} Q + \frac{\Phi^2}{1 - \Phi^2} (\bar{\beta} - \beta_0) Q$
Case 4	$\frac{\Phi}{1 + \Phi} [Q + (\bar{\beta} - \beta_0)t^*]$	$\frac{1}{N} \left[\frac{Q}{1 - \Phi^2} + (\bar{\beta} - \beta_j)t^* + \frac{\Phi^2}{1 - \Phi^2} (\bar{\beta} - \beta_0)t^* \right]$	$\bar{\beta} Q - \sigma^2 t^* + \frac{\Phi^2}{1 - \Phi^2} (\bar{\beta} - \beta_0) [Q + (\bar{\beta} - \beta_0)t^*]$

The results in Table C.1 illustrate the interaction between market power and the emission externality. First, case 1 shows that perfect competition without carbon pricing yields higher emissions than case 1. Second, imperfect competition without carbon pricing (case 3) can coincidentally achieve the first-best (case 2) emission level if the dominant firm has a higher carbon intensity than the rest of the sector ($\beta_0 > \bar{\beta}$). In contrast, Pigouvian taxation at the social cost of carbon with imperfect competition (case 4) does not yield the first-best level of emissions unless the dominant firm has a similar carbon intensity as the rest of the sector ($\beta_0 = \bar{\beta}$).

C.3 TPS with imperfect competition

We now turn to TPS and consider several sectors covered in TPS, each with a single benchmark. Again, we denote $\hat{\beta}_i$ the benchmark enforced in sector i .

In contrast to situations without carbon pricing or with a Pigouvian tax, we find that total carbon emissions under a TPS with a single benchmark per sector are not affected by market power. In addition, using intra-sectoral TPS or expanding the trading scope of the TPS across the whole economy does not change the total emissions.

Proposition 6 (Emissions under TPS with imperfect competition). *When each sector faces a single emission standard, the total amount of emissions in equilibrium under a TPS mechanism is:*

$$E = \sum_i \hat{\beta}_i Q_i$$

This level of emissions is reached:

- *whether sectors are perfectly competitive or consist of a dominant firm with a competitive fringe.*
- *whether firms are allowed or not to trade carbon allowances with other firms outside of their sector.*

Proof. See Appendix K. □

In the absence of subsector-specific benchmarks, expanding the scope of allowance trading does not change aggregate emissions under inelastic demand assumption. Whether or not this is a welfare-improving move thus depends on whether private production costs decrease. Proposition 1 showed this is indeed the case in the absence of market power. Imperfect competition seems very unlikely to change this result: moving from intra-sector to inter-sector trading does not change the amount of market power that the dominant firm has in the output market and seems likely to dilute any market power it may have in the allowance market.

D Political acceptability

This Appendix discusses political acceptability constraints. We focus on the case of a single sector, and thus drop the index i to simplify notations. We further assume for simplicity that abatement technologies are not available.

Subsectors consist of firms with similar while still heterogeneous carbon intensities. As a result, we expect the within-subsector heterogeneity in emission intensities to be small relative to sector-wide heterogeneity. In other words, it is reasonable to assume that:

$$\forall s \in i, \sigma_s^2 \ll \sigma^2 \tag{D.1}$$

where σ^2 is the sector-wide variance in emission intensities (the index i being dropped to simplify notations).

We define a “political acceptability” constraint as follows.

Assumption 1 (Political acceptability). *A carbon-trading mechanism is deemed “politically acceptable” if the decrease in the total profit of the most hit subsector is lower than $L\%$ relative to the laissez-faire benchmark.*

Without loss of generality, we assume that the subsectors are ordered from the most carbon-intensive to the least carbon-intensive:

$$\bar{\beta}_1 > \bar{\beta}_2 > \dots > \bar{\beta}_S$$

Proposition 7 (Maximum achievable emission reductions). *The maximum achievable emission reduction in the TPS with sector-specific benchmarks under the political acceptability constraint is:*

$$\frac{\sigma^2 L}{2\bar{\beta}(\bar{\beta}_1 - \bar{\beta})}$$

Pigouvian taxation can however achieve this emission reduction without making the political acceptability constraint bind, even when none of the tax revenue is redistributed to firms.

In contrast, if subsector-specific benchmarks $\hat{\beta}_s$ are implemented and $\alpha_s \bar{\beta}_s = \alpha_{s'} \bar{\beta}_{s'}$ for all s, s' , then the political acceptability constraint does not bind and achievable emission reductions are only constrained by individual firms' closures.

Proof. See Appendix [K](#). □

E Subsector disaggregation

Table E.1: Subsector disaggregation in numerical model

Sector	Technology Category	Subsector
Electricity	Coal-fired (other than CFB)	C1- 1000MW Ultra-supercritical
		C2 - 600MW Ultra-supercritical
		C3 - 600MW Supercritical
		C4 - 300MW Supercritical
		C5 - 600MW Subcritical
		C6 - 300MW Subcritical
		C7 - install capacity less than 300MW
	Circulating Fluidized Bed (CFB)	C8 - CFB Units (≥ 300 MW)
		C9 - CFB Units (≤ 300 MW)
	Gas-fired	C10 - F-class
		C11 - Pressure lower than F-class
Other	Wind power	
	Solar power	
	Hydro power	
	Nuclear power	
Cement	High efficiency	Intensity < 0.8446 (tCO ₂ /ton)
	Middle efficiency	$0.8446 \leq$ Intensity < 0.9144 (tCO ₂ /ton)
	Low efficiency	Intensity ≥ 0.9144 (tCO ₂ /ton)
Aluminum	High efficiency	Intensity < 8.00 (tCO ₂ /ton)
	Middle efficiency	$8.00 \leq$ Intensity < 8.33 (tCO ₂ /ton)
	Low efficiency	Intensity ≥ 8.33 (tCO ₂ /ton)
Iron & steel	Basic oxygen steelmaking - low efficiency	Intensity < 1.41 (tCO ₂ /ton)
	Basic oxygen steelmaking - middle efficiency	$1.41 \leq$ Intensity < 1.98 (tCO ₂ /ton)
	Basic oxygen steelmaking - high efficiency	Intensity ≥ 1.98 (tCO ₂ /ton)
	Electric arc furnace - low efficiency	Intensity < 0.125 (tCO ₂ /ton)
	Electric arc furnace - middle efficiency	$0.125 \leq$ Intensity < 0.235 (tCO ₂ /ton)
	Electric arc furnace - high efficiency	Intensity ≥ 0.235 (tCO ₂ /ton)

F Benchmarks in numerical model

Table F.1: Benchmarks (tCO₂/MWh or tCO₂/ton)

Sector	Subsectors	Benchmarks in the first year when the sector is added to TPS
Electricity	Coal-fired \leq 300MW	0.979
	Coal-fired $>$ 300MW	0.877
	Circulating fluidized bed	1.146
	Gas-fired	0.392
Cement	Low efficiency	0.833
	Medium efficiency	
	High efficiency	
Iron & Steel	Basic oxygen furnace – low efficiency	0.0165
	Basic oxygen furnace – medium efficiency	
	Basic oxygen furnace – high efficiency	
	Electric arc furnace – low efficiency	0.0037
	Electric arc furnace – medium efficiency	
Electric arc furnace – high efficiency		
Aluminum	Low efficiency	7.777
	Medium efficiency	
	High efficiency	
Paper & pulp	/	0.339
Oil refinery	/	0.281
Raw chemicals	/	0.617
Other non-metal	/	0.392
Other non-ferrous	/	0.342

G Sectoral marginal abatement costs and emission reductions

As indicated by the allowance prices in Figure G.1, the aluminum sector has the highest marginal abatement cost, so it is the sector in which reducing emissions is the most difficult. The high abatement costs in the aluminum sector is due to its high reliance on the electricity input, with the electricity input accounting for about 40% of the its total inputs. The increase in the electricity price significantly drives up aluminum’s production cost. The high reliance also makes it hard for the aluminum sector to substitute away from the electricity input. The cement sector also has high allowance price, because of the difficulty to reduce its emissions that emit from production process instead of fuel combustion. The electricity sector has close marginal abatement costs compared to the cement sector. The iron & steel sector has low allowance price, and it is the only sector that has lower price than the uniform allowance price in the inter-sectoral trading case among all Phases 1 & 2 sectors, implying that iron & steel sector has large allowance surplus to sell when trading scope broadens. Phase 3 sectors generally have lower allowance price than Phases 1 & 2 sectors.

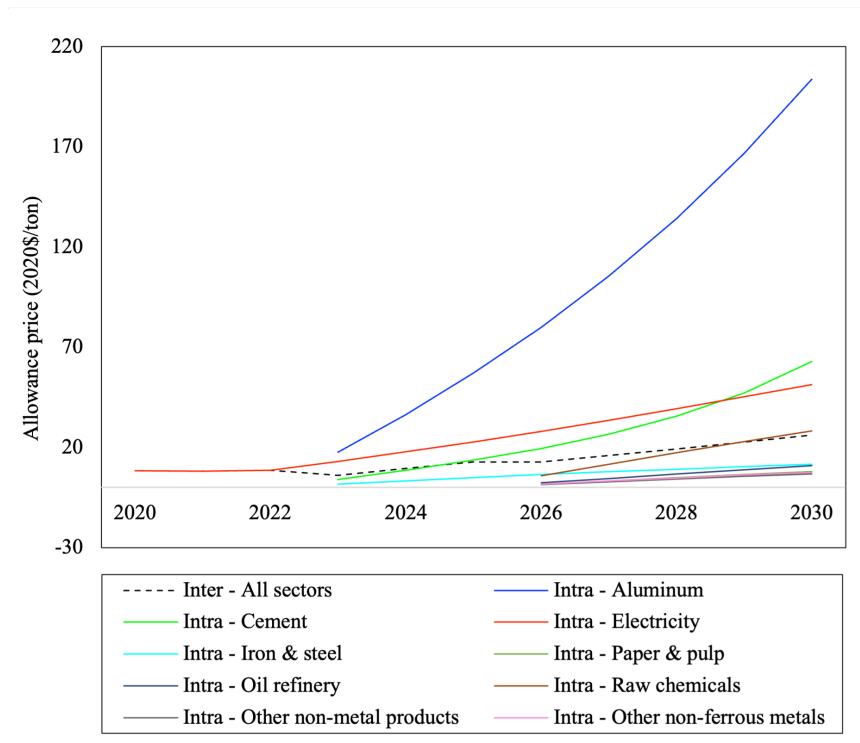


Figure G.1: Allowance prices.

How does the sectoral marginal abatement cost correlate with emission reduction? Figure G.2 displays the cumulative emission reductions by sector over the 2020-2030 interval, relative to baseline. The electricity sector experiences the largest emission reductions. Since aluminum has highest allowance price while negligible targeted emission reduction, broader trading increases emissions, predicted by Proposition 2.

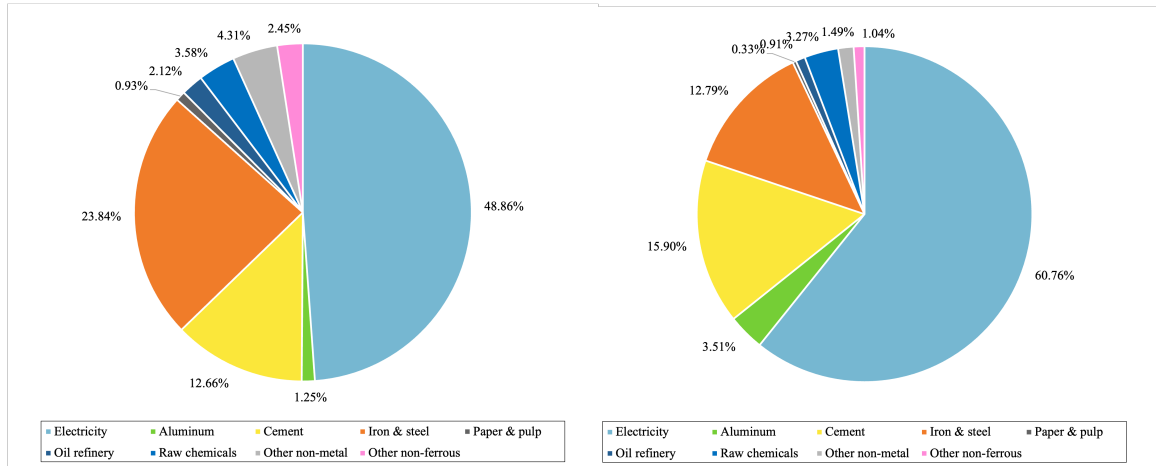


Figure G.2: **Covered-sectors' cumulative emission reductions in 2020-2030.** Left: inter-sectoral trading case; Right: intra-sectoral trading case

H Distributional impacts

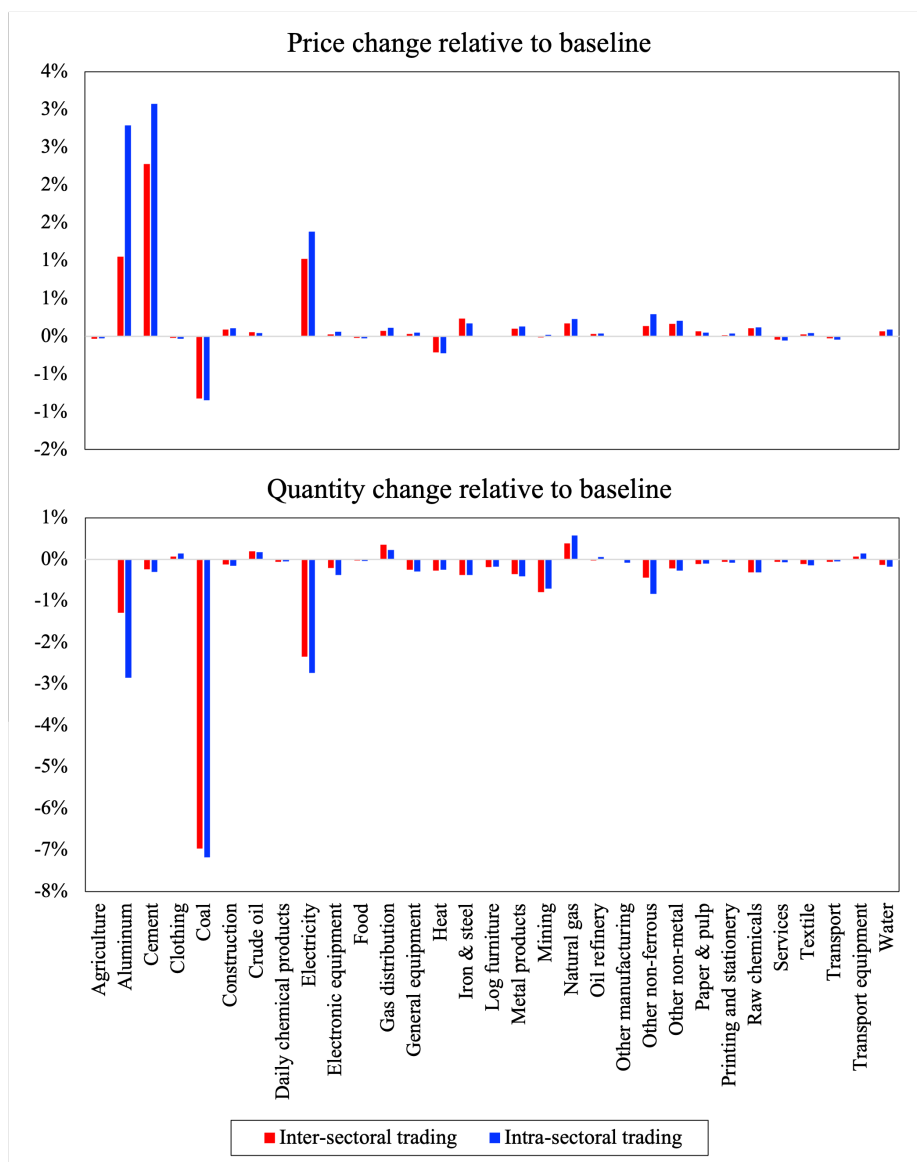


Figure H.1: Cumulative price and quantity changes relative to baseline over 2020-2030. Prices are expressed in real terms, where the price of the composite consumption good is employed as the price index.

I Within-sector benchmark heterogeneity

Table I.1: Private cost and emission reduction under the uniform within-sector benchmark case

year	Private cost (billion 2020\$)		Emission reduction (million ton)	
	Inter-sectoral	Intra-sectoral	Inter-sectoral	Intra-sectoral
2020	0.25	0.25	98	98
2021	0.32	0.32	121	121
2022	0.36	0.36	133	133
2023	0.91	0.96	270	273
2024	1.76	1.99	417	422
2025	2.83	3.49	569	577
2026	4.21	5.71	767	778
2027	6.01	8.67	966	985
2028	8.05	12.45	1168	1198
2029	10.32	17.19	1375	1419
2030	12.78	23.05	1581	1643
Total	47.77	74.44	7464	7647
Difference	26.66		182	

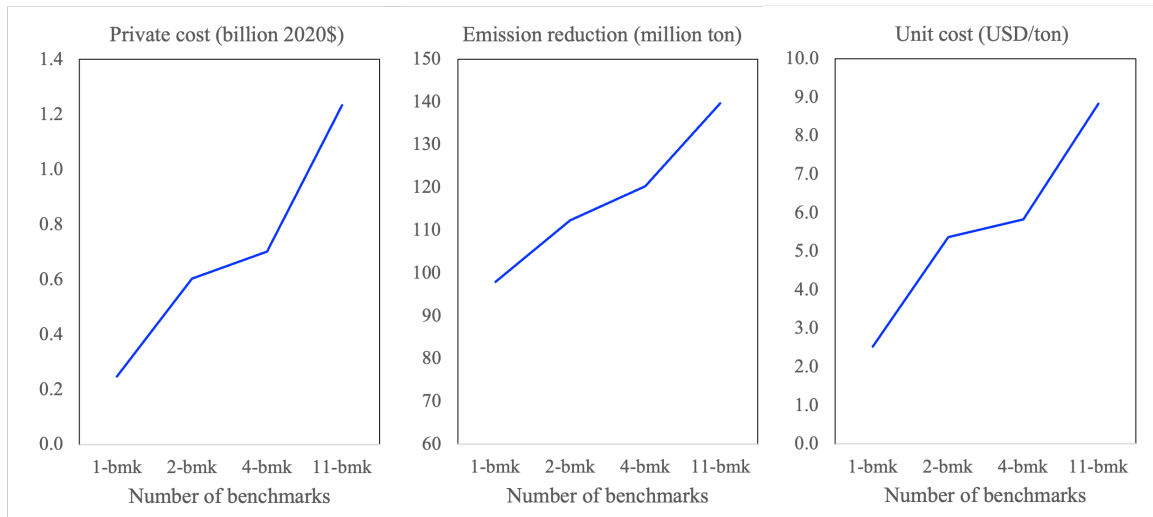


Figure I.1: **Private cost and emission reduction under different heterogeneity levels of benchmarks within the electricity sector in 2020.**

J Sensitivity analysis results

Table J.1: Private cost and emission reduction under uniform within-sector benchmark case

year	Private cost (billion 2020\$)		Emission reduction (million ton)	
	Inter-sectoral	Intra-sectoral	Inter-sectoral	Intra-sectoral
2020	0.19	0.19	89	89
2021	0.12	0.12	77	77
2022	0.12	0.12	83	83
2023	0.45	0.43	180	178
2024	0.94	1.02	282	277
2025	1.61	1.94	386	379
2026	2.27	3.27	493	492
2027	3.27	5.10	613	608
2028	4.47	7.52	736	727
2029	5.84	10.66	861	849
2030	7.40	14.77	987	974
Total	26.67	45.14	4784	4733
Difference		18.47		-51

Table J.2: Private cost and emission reduction with low abatement costs^a

year	Private cost (billion 2020\$)		Emission reduction (million ton)	
	Inter-sectoral	Intra-sectoral	Inter-sectoral	Intra-sectoral
2020	0.68	0.68	122	122
2021	0.80	0.80	140	140
2022	0.90	0.90	156	156
2023	1.45	1.97	284	312
2024	2.82	3.63	448	479
2025	4.65	5.89	621	655
2026	6.49	9.05	832	880
2027	9.48	13.07	1061	1112
2028	13.05	18.04	1299	1352
2029	17.24	24.06	1549	1603
2030	21.98	31.20	1803	1858
Total	79.52	109.29	8314	8668
Difference	29.76		354	

^a The energy-factor substitution elasticity in this scenario is 20% higher than the central case, meaning it is easier to substitute away from energy input in production.

Table J.3: Private cost and emission reduction with high abatement costs^a

year	Private cost (billion 2020\$)		Emission reduction (million ton)	
	Inter-sectoral	Intra-sectoral	Inter-sectoral	Intra-sectoral
2020	0.73	0.73	118	118
2021	0.85	0.85	134	134
2022	0.95	0.95	148	148
2023	1.48	2.12	271	296
2024	2.96	4.00	428	456
2025	5.00	6.64	594	623
2026	6.79	10.35	795	835
2027	10.08	15.19	1015	1054
2028	14.10	21.30	1244	1280
2029	18.90	28.92	1484	1515
2030	24.44	38.05	1731	1755
Total	86.30		7963	
Difference	42.80		252	

^a The energy-factor substitution elasticity in this scenario is 20% lower than the central case

K Proofs

K.1 Analytical expressions for PC_{intra} , PC_{inter} , E_{intra} and E_{inter}

K.1.1 Intra-sectoral allowance trading

If t_i denotes the emission allowance price in sector i and p_i the output price, firm $j \in s$ solves:

$$\max_{q,a} p_i q - \frac{1}{2} \left[N_i q^2 + \frac{q}{\mu_i} a^2 \right] - (\beta_j - a - \hat{\beta}_s) q t_i$$

From the first-order conditions, we have:

$$a = \mu_i t_i \quad (\text{K.1})$$

and:

$$q_j = \frac{1}{N_i} \left[p_i - (\beta_j - \bar{\beta}_s) t_i - \alpha_s \bar{\beta}_s t_i + \frac{1}{2} \mu_i t_i^2 \right] \quad (\text{K.2})$$

Summing this equation over all firms in the sector implies:

$$p_i = Q_i + \langle \alpha \bar{\beta} \rangle_i t_i - \frac{1}{2} \mu_i t_i^2 \quad (\text{K.3})$$

So that, for firm $j \in s$:

$$q_j = \frac{1}{N_i} \left[Q_i - (\beta_j - \bar{\beta}_s) t_i + (\langle \alpha \bar{\beta} \rangle_i - \alpha_s \bar{\beta}_s) t_i \right] \quad (\text{K.4})$$

The equilibrium allowance price is then obtained from the market-clearing condition in the allowance market:

$$\sum_{s \in i} \sum_{j \in s} (\beta_j - \mu_i t_i - \hat{\beta}_s) q_j = 0 \quad (\text{K.5})$$

From which we can derive:

$$t_i = \frac{\langle \alpha \bar{\beta} \rangle_i}{\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2} Q_i \quad (\text{K.6})$$

The sector total private costs PC_{intra} and emissions E_{intra} are then derived from the expression for t_i and the equilibrium output q_j of each firm:

- Total private supply cost for sector i is:

$$PC_{intra} = \frac{1}{2} \sum_i \left[1 + \frac{\langle \alpha \bar{\beta} \rangle_i^2}{\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2} \right] Q_i^2$$

- Total emissions are:

$$E_{intra} = \sum_i \left[\bar{\beta}_i - \frac{\langle \alpha \bar{\beta} \rangle_i}{\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2} (\langle \sigma^2 \rangle_i + \mu_i Q_i + \langle \alpha \bar{\beta}^2 \rangle_i - \bar{\beta}_i \langle \alpha \bar{\beta} \rangle_i) \right] Q_i$$

K.1.2 Inter-sectoral allowance trading

Under the inter-sectoral allowance trading, the price t of emission allowances is common across all the sectors participating in the mechanism. The price of the output market p_i is however sector-specific. Firm j in subsector s of sector i solves:

$$\max_{q,a} p_i q - \frac{1}{2} \left[N_i q^2 + \frac{q}{\mu_i} a^2 \right] - (\beta_j - a - \hat{\beta}_s) q t \quad (\text{K.7})$$

The first-order conditions are then:

$$a_j = \mu_i t \quad (\text{K.8})$$

and:

$$p_i = N_i q_j - \frac{1}{2} \mu_i t^2 + (\beta_j - \bar{\beta}_s) t + \alpha_s \bar{\beta}_s t \quad (\text{K.9})$$

Summing this equation for all firms $j \in i$ and dividing by N_i , we get:

$$p_i = Q_i + \langle \alpha \bar{\beta} \rangle_i t - \frac{1}{2} \mu_i t^2 \quad (\text{K.10})$$

Inserting this expression into the first-order condition for firm j , we can express the output production q_j of firm j as a function of the allowance price:

$$q_j = \frac{1}{N_i} [Q_i + ((\bar{\beta}_s - \beta_j) + \langle \alpha \bar{\beta} \rangle_i - \alpha_s \bar{\beta}_s) t] \quad (\text{K.11})$$

From the market-clearing condition of the allowance mechanism:

$$\sum_i \sum_{s \in i} \sum_{j \in s} (\beta_j - \mu_i t - \hat{\beta}_s) q_j = 0 \quad (\text{K.12})$$

we can then retrieve the equilibrium allowance price:

$$t = \frac{\sum_i \langle \alpha \bar{\beta} \rangle_i Q_i}{\sum_i (\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2)} \quad (\text{K.13})$$

and the output price in sector i is obtained from Equation (K.10).

Finally, economy-wide private production costs and emissions can be derived from the equilibrium output of each firm. We get:

$$PC_{inter} = \frac{1}{2} \sum_i Q_i^2 + \frac{1}{2} \frac{(\sum_i \langle \alpha \bar{\beta} \rangle_i Q_i)^2}{\sum_i (\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2)} \quad (\text{K.14})$$

and:

$$E_{inter} = \sum_i \bar{\beta}_i Q_i - \left(\sum_i (\langle \sigma^2 \rangle_i + \mu_i Q_i + \langle \alpha \bar{\beta}^2 \rangle_i - \langle \alpha \bar{\beta} \rangle_i \bar{\beta}_i) \right) \left(\frac{\sum_i \langle \alpha \bar{\beta} \rangle_i Q_i}{\sum_i (\langle \sigma^2 \rangle_i + \mu_i Q_i + \Omega_i^2)} \right) \quad (\text{K.15})$$

For the analytical expressions of total emissions, we further note that:

$$\langle \sigma^2 \rangle_i + \mu_i Q_i + \langle \alpha \bar{\beta}^2 \rangle_i - \langle \alpha \bar{\beta} \rangle_i \bar{\beta}_i = \sigma_i^2 + \mu_i Q_i - \tilde{\sigma}_{i, \bar{\beta} \hat{\beta}}$$

K.2 Proof of Proposition 4

The equilibrium social cost for a single sector under TPS is:

$$\begin{aligned} SC &= PC + Et^* \\ &= \frac{1}{2} \left[1 + \frac{\langle \alpha \bar{\beta} \rangle^2}{\langle \sigma^2 \rangle + \mu Q + \Omega^2} \right] Q^2 + \left[\bar{\beta} - \frac{\langle \alpha \bar{\beta} \rangle}{\langle \sigma^2 \rangle + \mu Q + \Omega^2} (\langle \sigma^2 \rangle + \mu Q + \langle \alpha \bar{\beta}^2 \rangle - \bar{\beta} \langle \alpha \bar{\beta} \rangle) \right] Q t^* \\ &= \frac{Q^2}{2} + \bar{\beta} Q + \frac{\frac{1}{2} \langle \alpha \bar{\beta} \rangle^2 Q^2 - \langle \alpha \bar{\beta} \rangle Q (\langle \sigma^2 \rangle + \mu Q + \langle \alpha \bar{\beta}^2 \rangle - \bar{\beta} \langle \alpha \bar{\beta} \rangle) t^*}{\langle \sigma^2 \rangle + \mu Q + \Omega^2} \\ &= \frac{Q^2}{2} + \bar{\beta} Q + \frac{1}{2} \frac{[\langle \alpha \bar{\beta} \rangle Q - (\langle \sigma^2 \rangle + \mu Q + \langle \alpha \bar{\beta}^2 \rangle - \bar{\beta} \langle \alpha \bar{\beta} \rangle) t^*]^2}{\langle \sigma^2 \rangle + \mu Q + \Omega^2} - \frac{(t^*)^2 (\langle \sigma^2 \rangle + \mu Q + \langle \alpha \bar{\beta}^2 \rangle - \bar{\beta} \langle \alpha \bar{\beta} \rangle)^2}{2 (\langle \sigma^2 \rangle + \mu Q + \Omega^2)} \end{aligned}$$

To simplify notations, let us denote:

$$A \equiv \langle \alpha \bar{\beta} \rangle Q - (\langle \sigma^2 \rangle + \mu Q + \langle \alpha \bar{\beta}^2 \rangle - \bar{\beta} \langle \alpha \bar{\beta} \rangle) t^*$$

Then:

$$SC = \frac{Q^2}{2} + \bar{\beta} Q + \frac{1}{2} \frac{A^2}{\langle \sigma^2 \rangle + \mu Q + \Omega^2} - \frac{(t^*)^2 (\langle \sigma^2 \rangle + \mu Q + \langle \alpha \bar{\beta}^2 \rangle - \bar{\beta} \langle \alpha \bar{\beta} \rangle)^2}{2 (\langle \sigma^2 \rangle + \mu Q + \Omega^2)}$$

We further note that, by definition of the different variables, we have:

$$\langle \sigma^2 \rangle + \Omega^2 = \sigma^2 + \langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 - 2 (\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle)$$

and:

$$\langle \sigma^2 \rangle + \langle \alpha \bar{\beta}^2 \rangle - \bar{\beta} \langle \alpha \bar{\beta} \rangle = \sigma^2 - \left(\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle \right)$$

Hence:

$$SC = \frac{Q^2}{2} + \bar{\beta}Q + \frac{1}{2} \frac{A^2}{\langle \sigma^2 \rangle + \mu Q + \Omega^2} - \underbrace{\frac{(t^*)^2}{2} \frac{\left(\sigma^2 + \mu Q - \left(\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle \right) \right)^2}{\sigma^2 + \mu Q + \langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 - 2 \left(\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle \right)}}_B$$

We then note than the term B may be rewritten as follows:

$$\begin{aligned} B &\equiv \frac{(t^*)^2}{2} \frac{\left(\sigma^2 + \mu Q - \left(\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle \right) \right)^2}{\sigma^2 + \mu Q + \langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 - 2 \left(\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle \right)} \\ &= \frac{(t^*)^2}{2} \left[\sigma^2 + \mu Q + \frac{\left(\sigma^2 + \mu Q - \left(\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle \right) \right)^2 - (\sigma^2 + \mu Q) \left(\sigma^2 + \mu Q + \langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 - 2 \left(\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle \right) \right)}{\langle \sigma^2 \rangle + \mu Q + \Omega^2} \right] \\ &= \frac{(t^*)^2}{2} \left[\sigma^2 + \mu Q + \frac{\left(\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle \right)^2 - (\sigma^2 + \mu Q) \left(\langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 \right)}{\langle \sigma^2 \rangle + \mu Q + \Omega^2} \right] \\ &= \frac{(t^*)^2}{2} \left[\sigma^2 + \mu Q + \frac{\left(\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle \right)^2 - \left(\langle \bar{\beta}^2 \rangle - \langle \bar{\beta} \rangle^2 \right) \left(\langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 \right) - (\sigma^2 + \mu Q) \left(\langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 \right)}{\langle \sigma^2 \rangle + \mu Q + \Omega^2} \right] \end{aligned}$$

Let us denote C the following quantity:

$$C \equiv (\langle \sigma^2 \rangle + \mu Q) \left(\langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 \right) + \left(\langle \bar{\beta}^2 \rangle - \langle \bar{\beta} \rangle^2 \right) \left(\langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 \right) - \left(\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle \right)^2$$

We finally get:

$$SC = \frac{Q^2}{2} + \bar{\beta}Q - \frac{1}{2}(\sigma^2 + \mu Q)(t^*)^2 + \frac{1}{2} \frac{A^2}{\langle \sigma^2 \rangle + \mu Q + \Omega^2} + \frac{(t^*)^2}{2} \frac{C}{\langle \sigma^2 \rangle + \mu Q + \Omega^2}$$

Importantly, the last two terms are non-negative. First, $A^2 \geq 0$ (squared real number) and the denominator $\langle \sigma^2 \rangle + \mu Q + \Omega^2$ is a sum of non negative terms. Second, to show that $C \geq 0$, we have from Cauchy-Schwartz inequality:

$$\langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 \geq 0$$

and:

$$\left(\langle \bar{\beta}^2 \rangle - \langle \bar{\beta} \rangle^2 \right) \left(\langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 \right) - \left(\langle \bar{\beta} \hat{\beta} \rangle - \langle \bar{\beta} \rangle \langle \hat{\beta} \rangle \right)^2 \geq 0$$

where this latter inequality follows the same logic as the proof that the covariance of two variables is lower or equal than the product of their standard deviations.

Therefore:

$$SC \geq \frac{Q^2}{2} + \bar{\beta}Q - \frac{1}{2}(\sigma^2 + \mu Q)(t^*)^2$$

and this lower bound is reached if, and only if, $A = C = 0$. A necessary condition for the latter equality ($C = 0$) is $\langle \hat{\beta}^2 \rangle - \langle \hat{\beta} \rangle^2 = 0$, which is equivalent to $\hat{\beta}_s$ being uniform. Conversely, if $\hat{\beta}_s$ is uniform, we have $C = 0$. Hence, $C = 0$ if, and only if, $\hat{\beta}_s$ is uniform. We denote $\hat{\beta}^*$ its value.

For a uniform benchmark $\hat{\beta}^*$, we then have:

$$A = (\bar{\beta} - \hat{\beta}^*)Q - (\sigma^2 + \mu Q) t^*$$

and thus $A = 0$ if, and only if:

$$\hat{\beta}^* = \bar{\beta} - (\sigma^2 + \mu Q) \frac{t^*}{Q}$$

Therefore setting $\beta_s = \bar{\beta} - (\sigma^2 + \mu Q) \frac{t^*}{Q}$ for all s achieves the lower bound of social cost and is the only way to do so.

K.3 Proof of Proposition 6

K.3.1 Intra-sectoral allowance trading

We first consider the intra-sectoral allowance trading case.

Market-clearing in the allowance market implies:

$$\sum_{j \in i} (\beta_j - \hat{\beta}_i) q_j = 0 \tag{K.16}$$

which may be rewritten:

$$\sum_{j \in i} \beta_j q_j = \hat{\beta}_i \sum_{j \in i} q_j \tag{K.17}$$

The left-hand side corresponds to total emissions E_i from sector i . Since total demand is assumed to be inelastic and to sum to Q_i , we have:

$$E_i = \hat{\beta}_i Q_i \tag{K.18}$$

Finally, summing this equation across all sectors, economy-wide emissions E are:

$$E = \sum_i \hat{\beta}_i Q_i \quad (\text{K.19})$$

K.3.2 Inter-sectoral allowance trading

Let's now consider the case where firms can exchange emission allowances with any firm in the economy.

The market-clearing equation for the inter-sectoral trading writes:

$$\sum_i \sum_{j \in i} (\beta_j - \hat{\beta}_i) q_j = 0 \quad (\text{K.20})$$

that is:

$$\sum_i \sum_{j \in i} \beta_j q_j = \sum_i \sum_{j \in i} \hat{\beta}_i q_j = \sum_i \hat{\beta}_i \sum_{j \in i} q_j = \sum_i \hat{\beta}_i Q_i \quad (\text{K.21})$$

Because the left-hand side term corresponds by definition to the total emissions E in the economy, we again have:

$$E = \sum_i \hat{\beta}_i Q_i \quad (\text{K.22})$$

Hence, the expression characterizing the total economy-wide emissions hold irrespectively of (i) whether it is intra-sectoral or inter-sectoral allowance trading; and (ii) whether each sector is perfectly competitive or has a dominant firm.

K.4 Proof of Proposition 7

K.4.1 Laissez-faire profit and emissions

In the absence of any carbon pricing mechanism, each firm produces a quantity $\frac{Q}{N}$. Total emissions are thus:

$$E^0 = \bar{\beta} Q \quad (\text{K.23})$$

The output market price is $p = Q$ so that the profit π_j^0 of a given firm is:

$$\pi_j^0 = \frac{1}{2} \frac{1}{N} Q^2 \quad (\text{K.24})$$

and the total profit Π_s^0 of subsector s is:

$$\Pi_s^0 = \frac{1}{2} \frac{n_s}{N} Q^2 \quad (\text{K.25})$$

K.4.2 TPS with sector-specific benchmarks

The equilibrium production of firm j when a TPS with a single emission standard is implemented is:

$$q_j = \frac{1}{N} \left[1 + (\bar{\beta} - \beta_j) \frac{\alpha \bar{\beta}}{\sigma^2} \right] Q \quad (\text{K.26})$$

Having solved for the equilibrium allowance price ($t = \frac{\alpha \bar{\beta}}{\sigma^2} Q$) and price ($p = \left[1 + \left(\frac{\alpha \bar{\beta}}{\sigma} \right)^2 \right] Q$), one can show that the equilibrium profit π_j^{TPS} of firm j is:

$$\pi_j^{TPS} = \frac{1}{2} \left(1 + (\bar{\beta} - \beta_j) \frac{\alpha \bar{\beta}}{\sigma^2} \right)^2 \frac{Q^2}{N} \quad (\text{K.27})$$

The total profit Π_s^{TPS} of a given subsector s is then:

$$\Pi_s^{TPS} \equiv \sum_{j \in s} \pi_j^{TPS} = \frac{1}{2} \left[\left(1 + (\bar{\beta} - \bar{\beta}_s) \frac{\alpha \bar{\beta}}{\sigma^2} \right)^2 + \left(\frac{\sigma_s}{\sigma} \right)^2 \left(\frac{\alpha \bar{\beta}}{\sigma} \right)^2 \right] \frac{n_s}{N} Q^2 \quad (\text{K.28})$$

By definition of the subsectors, we have $\frac{\sigma_s}{\sigma} \ll 1$ so that we may use the following approximation:

$$\Pi_s^{TPS} \simeq \frac{1}{2} \left(1 + (\bar{\beta} - \bar{\beta}_s) \frac{\alpha \bar{\beta}}{\sigma^2} \right)^2 \frac{n_s}{N} Q^2 \quad (\text{K.29})$$

The relative change in profits for subsector s is then:

$$\frac{\Pi_s^{TPS} - \Pi_s^0}{\Pi_s^0} = \left(1 + (\bar{\beta} - \bar{\beta}_s) \frac{\alpha \bar{\beta}}{\sigma^2} \right)^2 - 1 \quad (\text{K.30})$$

As expected, the subsector with the highest carbon intensity, assumed by convention to be subsector 1, suffers the highest loss in profit (in relative terms). In addition, this loss is increasing in the emission standard stringency α . As a result, the political acceptability constraint puts an upper bound α^M to the feasible emission standard stringency. This upper bound is such that:

$$\left(1 + (\bar{\beta} - \bar{\beta}_s) \frac{\alpha^M \bar{\beta}}{\sigma^2} \right)^2 - 1 = -L \quad (\text{K.31})$$

That is:

$$\alpha^M = \frac{\sigma^2}{\bar{\beta}(\bar{\beta} - \beta_1)} \left(\sqrt{1 - L} - 1 \right) \simeq \frac{\sigma^2 L}{2\bar{\beta}(\bar{\beta}_1 - \bar{\beta})} \quad (\text{K.32})$$

where the latter approximation is valid for low enough values of the maximum profit loss L (as a positive percentage) politically acceptable.

Finally, the total relative decrease in emissions enabled by the TPS mechanism is:

$$\frac{E^0 - E^{TPS}}{E^0} = \alpha \quad (\text{K.33})$$

so that the maximum achievable emission reduction achievable under the political acceptability constraint is α^M .

K.4.3 Pigouvian taxation

Under a Pigouvian tax t , firm j solves the following problem:

$$\max_q pq - \frac{1}{2} Nq^2 - \beta_j qt$$

From the first-order conditions and market-clearing equation we get:

$$q_j = \frac{1}{N} [Q + (\bar{\beta} - \beta_j)t] \quad (\text{K.34})$$

Total emissions are thus:

$$E^P(t) = \sum_j \beta_j q_j(t) = \bar{\beta} Q - \sigma^2 t \quad (\text{K.35})$$

So that the relative decrease in emissions achieved by a Pigouvian tax t is:

$$\frac{E^0 - E^P(t)}{E^0} = \frac{\sigma^2}{\bar{\beta} Q} t \quad (\text{K.36})$$

To achieve relative emission reductions equal to maximum emission reductions achievable under the TPS mechanism, one needs to put a carbon tax weakly higher than the threshold tax \hat{t} defined as:

$$\frac{\sigma^2}{\bar{\beta} Q} \hat{t} \equiv \alpha^M = \frac{\sigma^2 L}{2\bar{\beta}(\bar{\beta}_1 - \bar{\beta})} \quad (\text{K.37})$$

that is:

$$\hat{t} = \frac{LQ}{2(\bar{\beta}_1 - \bar{\beta})} \quad (\text{K.38})$$

We take a conservative approach and assume that the revenue from the tax is not recycled

within the sector. The profit π_j^P realized by firm j is then:

$$\pi_j^P = \frac{1}{2N} [Q + (\bar{\beta} - \beta_j)t]^2 \quad (\text{K.39})$$

so that the total profit Π_s^P of subsector s is:

$$\Pi_s^P \equiv \sum_{j \in s} \pi_j^P = \frac{1}{2} \frac{n_s}{N} \left[(Q + (\bar{\beta} - \bar{\beta}_s)t)^2 + \sigma_s^2 t^2 \right] \quad (\text{K.40})$$

Again, the most hit subsector is the one with the highest carbon intensity, that is subsector 1. At the threshold level \hat{t} of the Pigouvian tax, we have:

$$\frac{\Pi_1^P(\hat{t}) - \Pi_1^0}{\Pi_1^0} = \left(1 - \frac{L}{2}\right)^2 + \frac{\sigma_1^2 L^2}{4(\bar{\beta}_1 - \bar{\beta})^2} - 1 > \left(1 - \frac{L}{2}\right)^2 - 1 \simeq -L \quad (\text{K.41})$$

where the later approximation is valid for $0 < L \ll 1$. Hence, the Pigouvian tax needed to decrease emissions by as much as the most stringent politically acceptable single-benchmark TPS does not make the political acceptability constraint bind. In other words, Pigouvian taxation can achieve higher emission reductions than a single-benchmark TPS under the political acceptability constraint, even without recycling any of the taxation revenue towards firms.

K.4.4 TPS with subsector-specific benchmarks

Finally, we consider a situation where each subsector faces a different benchmark $\hat{\beta}_s$. We further assume that subsector-level standards have the same stringency in the following sense:

$$\forall s, s' \text{ we have } \alpha_s \bar{\beta}_s = \alpha_{s'} \bar{\beta}_{s'}$$

In other words, $\alpha_s \equiv \frac{A}{\bar{\beta}_s}$ where A is a common scalar capturing the overall stringency of the mechanism.

Firm j in subsector s now solves:

$$\max_q pq - \frac{1}{2} N q^2 - (\beta_j - \hat{\beta}_s) q t$$

The first-order condition then writes:

$$p - N q_j - (\beta_j - \hat{\beta}_s) t = 0 = p - N q_j - (\beta_j - \bar{\beta}_s) t - \alpha_s \bar{\beta}_s t$$

Summing first-order conditions over firms and dividing by N , we get:

$$p - Q - At = 0 \quad (\text{K.42})$$

Hence:

$$q_j = \frac{1}{N} [Q + (\bar{\beta}_s - \beta_j)t] \quad (\text{K.43})$$

The equilibrium allowance price is obtained by solving:

$$\sum_{s \in i} \sum_{j \in s} (\beta_j - \hat{\beta}_s) q_j = 0 \quad (\text{K.44})$$

which yields:

$$t = \frac{AQ}{\langle \sigma^2 \rangle} \text{ where we defined: } \langle \sigma^2 \rangle \equiv \frac{1}{N} \sum_{s \in i} n_s \sigma_s^2 \quad (\text{K.45})$$

From the equilibrium output price p , allowance price t and production level q_j of firm j , one can derive the profit π_j of firm $j \in s$:

$$\pi_j = \frac{1}{2} \left(1 + (\bar{\beta}_s - \beta_j) \frac{A}{\langle \sigma^2 \rangle} \right)^2 \frac{Q^2}{N} \quad (\text{K.46})$$

The aggregate profit Π_s^{mTPS} of subsector s is then:

$$\Pi_s^{mTPS} = \frac{1}{2} \frac{n_s}{N} \left[1 + \left(\frac{\sigma_s A}{\langle \sigma^2 \rangle} \right)^2 \right] Q^2 > \Pi_s^0 \quad (\text{K.47})$$

Because the profit of each subsector actually increases relative to the status quo, the political acceptability constraint does not bind.

Finally, one can show that total emission reductions amount to $\frac{A}{\beta}$ relative to the status quo, so that emissions can be decreased by an arbitrary amount as long as A remains sufficiently low not to induce a firm to shut down.