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Linking Cap-and-Trade Systems with Heterogeneous Co-Benefits from Abatement

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Abstract

Expanding the coverage of cap-and-trade systems is essential for improving global environmental outcomes and can lower the economic costs of achieving climate goals. However, linking cap-and-trade systems to new sectors presents various challenges for policymakers. This paper develops a theoretical model to study the linkage of existing markets to new sectors using two policy instruments: new emissions permit allocations and trading ratios. I show that first-best outcomes can be achieved by (i) setting trading ratios equal to the ratio of co-benefits from abatement between sectors and (ii) setting new permit allocations based on the efficiency of the existing cap. Importantly, regulators cannot achieve first-best solutions if there are constraints on one of these policy instruments. Leveraging my theoretical model, I simulate the European Union Emissions Trading System's decision to link its cap-and-trade system to the aviation sector. Using estimates from the EU, this paper quantifies welfare from the initial linkage and demonstrates that alternative choices of trading ratios and permit allocations could have improved welfare by over €640 million annually.

1 Introduction

In the ongoing global battle against climate change, market-based regulations designed to price greenhouse gas (GHG) emissions have emerged as pivotal regulatory tools. Among the most widely used of these regulations are cap-and-trade (CAT) systems. The concept of CAT appeals to economists and policymakers alike because of its cost-effectiveness. These emissions trading systems allow firms the flexibility to reach their own abatement requirements while ensuring the aggregate abatement targets are fulfilled at the lowest possible cost. With the help of environmental economists, systems such as the U.S. Sulfur dioxide (SO_2) cap-and-trade program have yielded substantial economic efficiency gains compared to command and control style regulations (Stavins, 1998; Ellerman, 2000). Although dozens of CAT systems have been developed over the last few decades, sustaining and improving these CAT systems comes with a variety of challenges.

Among the challenges associated with improving existing CAT systems is determining which sectors of the economy to regulate. Typically, CAT systems begin by regulating only a portion of polluting sectors within a region, such as electricity generation.[1] Once established, the new policy goal for regulators is to expand these systems to encompass a broader range of emissions sources. Expanding these systems through linkage to new sectors can offer economic, political, and administrative benefits; however, regulators should be mindful that abatement across different sectors may not yield consistent marginal benefits (Schneider et al., 2017; Muller, 2012). As a result, linking CAT systems may alter the distribution of emissions across sectors, potentially impacting the overall efficiency of the system.

In this paper, I develop a theoretical model to analyze how policy choices can impact the efficiency of linking an existing cap-and-trade system to a new sector. When linking with a new sector, regulators have two main choice variables that affect the efficiency of the policy: the allocation of emissions permits and the trading ratio. First, the regulator decides how many permits to distribute to this sector. This allocation represents the "cap" of cap-and-trade for the newly regulated sector. Without a permit, firms can either reduce their own emissions or purchase permits from another firm. Second, the regulators must choose a trading ratio. This trading ratio dictates how permits from one sector can be exchanged for permits from the other sector. With this new theoretical framework, I investigate how regulators should think not only about setting trading ratios and new

[1] In 2024, the European Union Emission Trading System only regulated around 40-45% of greenhouse gas emissions within the EU (European Environmental Agency, (EEA), 2024

permit allocations independently but also how the relationship between these choices will impact the efficiency of the entire system. Unlike linkages of cap-and-trade systems across regions with different governing authorities, extending existing CAT systems to new sectors within the same region grants regulators the ability to control both the trading ratio and new emissions allocation decisions.[2] This scenario of linking existing cap-and-trade systems to new sectors is a distinct policy framework where economics can provide valuable insights for policymakers.

When designing these systems, policymakers have followed the standard approach to treat damages caused by greenhouse gas emissions independent of source and location. Therefore, emissions permit prices are constant across all regulated firms, with trading ratios equal to one. However, recent literature has recognized that abatement of GHG emissions often coincides with abatement of co-pollutants from that source. The health and environmental damages of co-pollutants, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), can vary over 100 times depending on their emission location (Muller and Mendelsohn, 2009). Because of this heterogeneity in co-benefits of abatement, regulators who fail to incorporate this variation into their policy design will be unable to achieve efficient policy outcomes. This paper asks the question, under what conditions can regulators achieve first-best outcomes when linking cap-and-trade systems to new sectors with heterogeneous co-benefits from abatement?

Akin to findings in the literature, I show that trading ratios equal to one are suboptimal in policies with heterogeneous damages across sectors or locations (Helm, 2003; Muller and Mendelsohn, 2009, Holland and Yates, 2015; Fowlie and Muller, 2019). Abatement of GHG emissions from one sector or region may have larger co-benefits than abatement from another sector due to the concentration or location of co-pollutants. For example, CO_2 emissions from an airplane flying over the Atlantic Ocean will cause the same marginal damages as CO_2 emissions from a factory in Germany. However, the burning of fossil fuels not only produces CO_2 emissions but also generates other pollutants. Abatement of CO_2 from an airplane may cause vastly different levels of abatement of co-pollutants than a factory or power plant. The damages caused by these co-pollutants will also vary based on their location and concentrations. I show that when linking CAT systems, trading ratios should be set to the ratio of marginal benefits and co-benefits between sectors. This ratio is essential for ensuring the efficiency of these CAT systems by shifting abatement from one sector of

[2] Linkages between CAT systems in different regions have had difficulties agreeing upon policy parameters and remain few and far between (Quemin and de Perthuis, 2019).

the economy to another.

Not only is it important for regulators to optimally set the trading ratio, but selecting the correct amount of permits to allocate to the new sector is crucial for an efficient linkage. It is often the case that regulators select this permit allocation based on a percentage of historical emissions from that sector.[3] No matter the number of permits allocated to the new sector, the CAT system will be cost-effective; however, the efficiency of these systems relies on the ability to equate the marginal damages from these emissions to the marginal costs of abatement.

In this paper, I show that selecting an optimal trading ratio and optimal emissions permit allocation together, instead of using traditional choices for these variables, can improve the welfare of these systems. I also demonstrate that optimal choices for the new sector's permit allocation and trading ratio can help recalibrate an existing system if it is operating inefficiently. With accurate information on marginal costs and damages across sectors, the extension of a new sector can be used as an instrument to realign an inefficient cap-and-trade system without changing limits on the existing sector. However, this realignment requires manipulating both the new sector's permit allocation and the trading ratio. If there are constraints on the choice of these parameters (i.e., a trading ratio that must be set to one), only manipulating one of these parameters will not lead to first-best outcomes.

Leveraging this theoretical model, I apply my findings to the European Union's decision to link its Emission Trading System (ETS) into the aviation sector. This linkage is a unique real-world example of how regions have chosen to expand coverage of their environmental regulations. In 2012, the EU expanded its ETS to include the aviation sector by allocating new permits to the aviation sector and allowing airlines to trade with other EU ETS sectors.[4] The decision to expand into the aviation industry is an important linkage to study for two reasons. First, the aviation sector has a relatively high marginal abatement cost curve, making airlines likely to buy permits from other existing emitters in the EU ETS when linked (Tang and Hu, 2019; Liu and Jiang, 2023). Second, marginal co-benefits from the abatement of aviation emissions are considered to be vastly different than those from stationary sources. This variation is due to the altitude and location of aviation emissions as well as the concentration of co-pollutants (Grobler et al., 2019; Lee et al., 2021). I explore how a change in the trading ratio or the amount of emissions permits allocated to

[3]This practice is known as "grandfathering".

[4]The linkage used a trading ratio equal to one, allowing aviation firms to buy permits from the existing EU ETS to count towards one ton of their CO_2 emissions; however, they could not sell aviation permits to other sectors.

the aviation sector would have impacted the welfare of this linking policy. Optimal choices of both policy parameters would have led to a €640 million increase in welfare from this linkage annually.

This paper contributes to three prominent strands of literature. First, I contribute to the broad literature on optimally designing cap-and-trade markets (Montgomery, 1972; Pizer, 2002; Flachsland et al., 2009). Rather than modeling how to design a system from scratch, this paper analyzes an increasingly common new policy scenario where cap-and-trade systems are expanding to new sectors. Second, this paper contributes to the literature on understanding the heterogeneous benefits of abatement across multiple emissions sectors (Muller, 2012; Groosman et al., 2011, Muller and Mendelsohn, 2009, Holland et al., 2011, Fowlie and Muller, 2019). I show that using trading ratios equal to one is often inefficient in these systems, even when systems are regulating uniformly mixed pollutants due to heterogeneous co-pollutants between sectors. Finally, this paper contributes to the literature studying the EU ETS policy to expand their cap-and-trade market into the aviation sector (Nava et al., 2018; Vespermann and Wald, 2011; Anger and Köhler, 2010; Fageda and Teixidó, 2022; Scheelhaase et al., 2021). This paper is the first to quantify how alternative policy parameter choices could have impacted the welfare of this cap-and-trade system.

The remainder of this paper is organized as follows. Section 2 outlines the related literature. Section 3 introduces a theoretical model of extending existing cap-and-trade systems to new sectors with differential marginal damages. Section 4 applies our theoretical model to simulate the EU ETS expansion into aviation and evaluate alternative policy choices. Section 5 discusses the implications of this paper, and Section 6 concludes.

2 Background and Literature Review

Environmental economists have developed carbon taxes and cap-and-trade systems as market-based approaches for pollution regulation. These policies have been implemented throughout the world in varying sizes and regions. The major reason climate economists prefer these market-based policies compared to traditional command and control style approaches is due to their cost-effectiveness. Over the past few decades, these groundbreaking systems have been able to achieve targeted emissions reductions at lower total costs compared to alternative emissions programs (Fowlie et al., 2012; Stavins, 1998; Ellerman, 2000; Schmalensee and Stavins, 2017 Keohane, 2009). The success of these systems has motivated economists and policymakers to link these existing programs to new sectors, expanding the coverage of these policies.

In 2022, there were 25 operational cap-and-trade systems designed around greenhouse gas emissions. These systems covered only 17% of global anthropogenic GHG emissions (ICAP, 2022). Most of these CAT systems exist independently within their region. On their own, these systems have been extremely effective in reducing emissions, however, growing these systems in size can open up opportunities to lower abatement costs. Similar to the trade literature, opening up opportunities to trade with other sectors or regions will lower total abatement costs (Krugman et al., 1980). This act of joining two or more systems to each other is defined as "linking". Linking describes the case where one system's or sector's allowances can be used directly or indirectly by another to comply with emissions regulations. Many theoretical papers have shown the potential benefits of linking cap-and-trade systems to increase the effectiveness of environmental policy and fight climate change (Flachsland et al., 2009; Burtraw et al., 2013; Ranson and Stavins, 2016; Ranson and Stavins, 2016, Anger, 2008). In this paper, I expand this literature by evaluating the linking of cap-and-trade markets to new sectors within the same region.

Linking cap-and-trade markets creates opportunities to trade emissions permits across sectors or regions with new firms that have lower abatement costs due to differences in technology, input prices, or other firm-specific factors. Although theoretically, linking two or more systems together will reduce costs, there are a variety of important design characteristics that need to be aligned in each of the cap-and-trade systems for these benefits to be realized. For example, incompatible price collars or banking abilities within these systems could negate the benefits of linkage (Schneider et al., 2017; Flachsland et al., 2011; Tuerk et al., 2009). In order for a linkage to be effective, systems must agree upon a trading ratio that represents the value that permits can be exchanged between markets. In practice, using a trading ratio of one is common. However, many studies have theorized the potential benefits of alternative trading ratios. Recently the literature has shown the potential benefits of using trading ratios other than one-for-one when linking regions with different marginal abatement costs (Woerman, 2023; Quemin and de Perthuis, 2019). Similarly, trading ratios equal to one are inefficient when markets have differences in marginal damages (Fowlie and Muller, 2019; Holland and Yates, 2015; Muller and Mendelsohn, 2009). These alternative choices of trading ratios may sacrifice the cost-effectiveness of these CAT markets; however, they provide overall net benefits by reducing total damages from emissions.

In practice, policymakers and economists have touted the benefits that CAT systems produce through lowering costs, while focus on efficiency has often been an afterthought. This paper extends upon the literature on improving the efficiency of cap-and-trade systems through a better understanding of marginal damages between different emissions sources. Efficiently designed CAT systems occur when the marginal benefits of abatement are equal to the marginal costs of abatement. When modeling CAT systems designed to reduce greenhouse gas emissions and their impact on climate change, it is important to distinguish where the costs and benefits are occurring. While these CAT systems are imposing higher costs on firms operating in the world today, the abatement of greenhouse gas emissions right now will reduce the damages these emissions will cause in the future. Therefore, in these models, CAT systems provide benefits by avoiding future damages from harmful greenhouse gas emissions. The benefits from abatement may not occur for that sector or region within the year or even the decade. These benefits from abatement may be seen by generations far in the future across the whole world.

CAT systems like the EU ETS, have primarily been designed around greenhouse gas pollutants such as CO_2. Often, these pollutants have been assumed to be uniformly mixed, and the damages of these emissions are independent of their source and location. However, recent research has shown two potential reasons that even pollutants, such as CO_2, can have heterogeneous marginal benefits from abatement depending on the sector they are produced in. One reason for the differences in marginal benefits from abatement comes from not the emissions of GHGs but the co-pollutants of GHG emissions. Often it is the case that air pollutants are not emitted independently. Pollutants, such as CO_2, are emitted in conjunction with co-pollutants that create damages locally. Consequently, abatement of CO_2 emission may also cause abatement from other local pollutants as well (Muller, 2012). Understanding the relationship between GHG emissions and co-pollutants that have harmful local damages is important to fully grasp the damages or benefits of CAT policies (Dedoussi et al., 2019; Zwickl et al., 2021). These co-pollutants can be either complements or substitutes for existing pollutants. Literature has shown that co-pollutants are often complements to the criteria pollutant (Bollen et al., 2009; Burtraw et al., 2003; Muller, 2012; Nemet et al., 2010). Due to this complementary relationship, benefits from abating greenhouse gas emissions may be much higher than previously expected while also being heterogeneous across sectors. For example, abatement of CO_2 from a coal power plant in a densely populated urban area will have vastly larger benefits than abatement of CO_2 from a rural natural gas power plant. The second reason for the differences in marginal benefits of abatement relies on the fact that high concentrations of greenhouse gas emissions, like CO_2, can lead to extreme weather and local human health impacts (Jacobson et al., 2019; Yang et al., 2021). Therefore, marginal benefits from abatement may be larger based on the location of those CO_2 emissions.

The main distinction between my model and previous research that examines linkages of cap-and-trade systems with differential marginal benefits from abatement is the fact that instead of analyzing the linkage of two existing systems, this model examines the linkage of an existing system to a new sector within the same region. For example, rather than joining the California cap-and-trade program with Quebec's system, our model explores the potential extension of the California system to a previously unregulated sector that has different marginal benefits than the existing regulated sectors. This style of policy has become more common in recent years in places like Europe where the EU ETS system expanded into aviation in 2012 and maritime emissions in 2024.

Linking an existing system to a new sector allows the regulators the ability to choose both a trading ratio between sectors and the new sectoral emissions permit allocations. In cross-country linkages of CAT systems, these policy choices would be subject to a variety of political or economic considerations which could lead to socially inefficient outcomes (Dijkstra et al., 2011). Schneider et al. (2017) postures that mutually agreeing upon a trading ratio could be a large political barrier to link systems. Allowing a single regulating authority to choose both parameters is crucial for achieving economically efficient outcomes. Using both of these characteristics, policymakers can think about the expansion of cap-and-trade systems to new sectors with differential marginal co-benefits in ways they previously may not have.

Our understanding of marginal costs and marginal benefits from emissions has grown due to the help of scientists and engineers, however, there is still a great deal of uncertainty when developing models to assess the potential abatement cost of emissions and the social cost of pollutants (Anthoff and Tol, 2013). This paper is not the first to study uncertainties within market-based pollution regulations. Weitzman's (1974) fundamental paper demonstrates how taxes and quantity-based instruments fail to be equivalent under uncertainty. Others have evaluated the importance of uncertainty in CAT systems with differential marginal damages. Fowlie and Muller (2019) examine the tradeoff between taxes and permits under uncertainty when pollution damages vary by source. Holland and Yates (2015) demonstrate how a trading ratio equal to the marginal damage ratio is generally not optimal for markets under uncertainty. I expand upon these studies to compare how policy choices differ in their ability to recalibrate a CAT system when marginal benefits or marginal costs manifest contrary to expectations.

3 Theoretical Model

In this section, I expand traditional emissions trading linkage models by evaluating when an existing system expands to a new sector with heterogeneous marginal benefits from abatement. Unlike the previous literature, which evaluates the linkage of two existing markets, this model analyzes the linkage of a new sector to an existing emissions trading system. This unique new sector possesses its own marginal abatement cost curve and marginal benefits curve. The difference in abatement costs for this sector may come from differences in abatement technology or availability of fuel switching. Differences in marginal benefits from abatement may come from differences in co-pollutants by sector. These marginal benefits from abatement can also be modeled as avoided future marginal damages from emissions. Regulators in this market then determine the allocation of emissions permits to this new sector and a trading ratio. I measure emissions similar to a standard carbon cap-and-trade system in which the units of emissions are measured by tonnes of carbon dioxide (CO_2) or carbon dioxide equivalents (CO_2e). This model provides a useful framework for thinking about using both trading ratios and new emissions permit allocations when incorporating new sectors into existing systems.

Suppose two sectors $i \in \{1, 2\}$, can be characterized by a representative firm that produces a fixed level of output by emitting CO_2 and other co-pollutants in the process. These firms have relative cost functions which are a function of their emissions e_i. Cost curves are represented as $K(E)$ such that:[5]

$$K_i(e_i) = \alpha_i - \beta_i e_i + \frac{\gamma_i}{2} e_i^2 \tag{1}$$

The parameters in each firm's cost function are assumed to be positive $\alpha, \beta, \gamma > 0$. In the absence of any emissions-restricting policy, firms will minimize their costs by producing emissions at the level of $E_i^{bau} = \frac{\beta_i}{\gamma_i}$. These cost functions can be rewritten in terms of abatement C(A_i).

$$C_i(A_i) = K(E^{bau} - A_i) - K(E^{bau}) \tag{2}$$

[5]For ease, I assume a quadratic functional form in our theoretical model. This functional form is used by others (Woerman, 2023; Quemin and de Perthuis, 2019).

Therefore, abatement costs C(A) can be expressed as $C_i(A_i) = \frac{\gamma}{2}A_i^2$ and marginal abatement costs can be expressed as $MC_i(A_i) = C_i'(A_i) = \gamma_i A_i$. This abatement cost function is increasing and convex in abatement ($C_i'(A) > 0$ and $C_i''(A) > 0$). I begin by assuming that the regulator has full information and can observe the firm's cost functions.

For our model, I assume that benefits (avoided damages) of abatement are linear and additively separable in source-specific abatement such that $D_i(A_i) = \delta_i A_i$. Source-specific marginal damages are then equal to δ_i. This assumes that abatement in one sector does not have the same benefits as abatement from another sector. For example, abatement from a coal-power plant may have different marginal benefits than abatement from a manufacturing facility due to differences in co-pollutants being abated in conjunction.[6] Estimates for the marginal damages of CO_2 emissions have been studied widely and assumed to be relatively constant. Other emissions, such as NO_x and SO_x, may have increasing marginal damage functions; however, for simplicity of this model, I assume they are constant. I assume that regulators, with the help of scientists, have a full understanding of source-specific damage functions for each sector in the cap-and-trade system. I later relax this assumption and evaluate policy choices under uncertainty.

As has been outlined in previous works, the first-best solution of cap-and-trade systems is for policymakers to maximize social welfare (Eq. 3). The first component of equation (3) measures the benefits of reduced damages from abatement. The second term measures the costs imposed on firms in order to complete some abatement activities compared to their business-as-usual emissions level. Intuitively, the first-order conditions of equation (4) imply that marginal damages should be set equal to marginal costs for each sector i.

$$max \;\; TSW = \sum_i D_i(A_i) - \sum_i C_i(A_i) \tag{3}$$

$$FOC: \quad D_i'(A_i) = C_i'(A_i) \; \forall i \tag{4}$$

In the case of two sectors, maximizing social welfare gives us the first-order conditions that $\gamma_1 A_1 = \delta_1$ and $\gamma_2 A_2 = \delta_2$. I will denote this solution to these first-order conditions as $A^* = \{A_1^*, A_2^*\}$. Optimal A^* takes the form $\{\frac{\delta_1}{\gamma_1}, \frac{\delta_2}{\gamma_2}\}$. Using this solution for A^*, I solve for optimal total

[6]In this model, I assume that co-pollutants like SO_x and NO_x (that have harmful local impacts) are complements to abatement of greenhouse gas emissions. This is consistent with findings in the literature; however, it may not be universal for all co-pollutants in all sectors.

social welfare.

$$TSW = \delta_1 A_1^* + \delta_2 A_2^* - \frac{\gamma_1}{2}(A_1^*)^2 - \frac{\gamma_2}{2}(A_2^*)^2 \tag{5}$$

$$TSW^* = \frac{\delta_1^2 \gamma_2 + \delta_2^2 \gamma_1}{2\gamma_1 \gamma_2} \tag{6}$$

Now suppose a cap-and-trade policy environment in which one sector has already been established, and policymakers are attempting to link a new sector to this system. Sector 1 has established an emissions cap represented by an abatement requirement $\bar{A}_1$. $\bar{A}_1$ represents the difference between the sectors business as usual emission E^{bau} minus the allocation of emissions permits to that sector w_i such that $\bar{A}_i = E_i^{bau} - w_i$.[7]

As per the standard emissions trading results the representative firm in Sector 1 will minimize their costs such that the price of a permit will be equal to the marginal cost $p_1 = C_1'(\bar{A}_1)$. This price p_1 will be observed by regulators when deciding how to integrate a new sector.

Incorporating a new sector, regulators will now require the new sector to surrender permits for their sector's emissions while allowing the two sectors to engage in trading. Before the integration, regulators have two policy variables to determine: the required new sector abatement, $\bar{A}_2$, and the trading ratio, r. The required abatement for this new sector is equivalent to the choice of how many emissions permits to allocate to this new sector. Selecting the number of permits will determine the total emissions from the new sector and, in turn, their required abatement to complete relative to their business-as-usual emissions levels. The trading ratio represents the number of Sector 1 permits that are equivalent to one permit in Sector 2. Alternatively, for each tonne of CO_2e produced by a firm in Sector 1, they are required to surrender one Sector 1 permit or $\frac{1}{r}$ permits from Sector 2.

In a linked market, the total abatement from the two sectors must satisfy this equality:

$$r(A_2 - \bar{A}_2) = \bar{A}_1 - A_1 \tag{7}$$

With permits being exchanged using a trading ratio of r, the prices of the permits must also be

[7] As regulators have information on business as usual emissions from each source, they can choose the allocation of permits w_i which corresponds to an abatement of $\bar{A}_i$

proportional to this ratio. Therefore no arbitrage opportunities will be available between sectors.

$$p_2 = rp_1 \tag{8}$$

Historically, regulators have used the approach of setting a new sector's required abatement ($\bar{A}_2$) at a small proportion of historical emissions. Regulators have been wary of not making the new regulation overly burdensome for the new sector. Therefore, they have typically allocated this new sector enough permits to cover a relatively high proportion of their historical emissions. For example, the EU ETS allocated permits equivalent to 95% of the aviation industry's historical emissions to firms when incorporating them into the cap-and-trade system.

For trading ratios, policymakers have typically chosen to use a trading ratio equal to 1. This standard approach was justified in carbon cap-and-trade markets due to the nature of carbon emissions being uniformly mixed.[8] However, when there are differences in marginal costs, marginal damages, or uncertainty, trading ratios equal to 1 can be sub-optimal (Holland and Yates, 2015; Woerman, 2023; Muller and Mendelsohn, 2007; Quemin and de Perthuis, 2019). This model builds on previous literature to examine not only the optimal choice for trading ratios, but also for the required abatement of the new sector ($\bar{A}_2$).

$$\begin{aligned} max_{r,\bar{A}_2}\, TSW &= \sum_{1}^{2} D_i(A_i) - \sum_{1}^{2} C_i(A_i) \\ s.t. \quad r(A_2 - \bar{A}_2) &= \bar{A}_1 - A_1 \quad \& \quad r \geq 0 \end{aligned} \tag{9}$$

When choosing choices for $\bar{A}_2$ and r, a regulator's goal would be to ensure that the cap-and-trade system is still operating at a first-best solution. Total social welfare is maximized when marginal damages are equal to marginal costs for each sector as shown in (Eq. 4). Optimal choices for these parameters vary based on the efficiency of the initial sector 1. First, I examine circumstances when the initial sector is already operating efficiently such that the marginal benefits from abatement are equal to the marginal costs ($D_1'(A_1^*) = C_1'(A_1^*)$).

[8]With trading ratio equal to one, prices in both sectors of the market will be equal to each other and also equal to the marginal costs of both sectors. This achieves the standard result of cost-effectiveness within a cap-and-trade system.

Proposition 1 *Under perfect information, if the initial sector emissions cap is set efficiently such that $A_1 = \frac{\delta_1}{\gamma_1}$, a first-best solution can be achieved by setting the new sector cap equal to $\bar{A}_2$ where $\bar{A}_2 = \frac{\delta_2}{\gamma_2}$, and the trading ratio equal to $r = \frac{\delta_2}{\delta_1}$,*

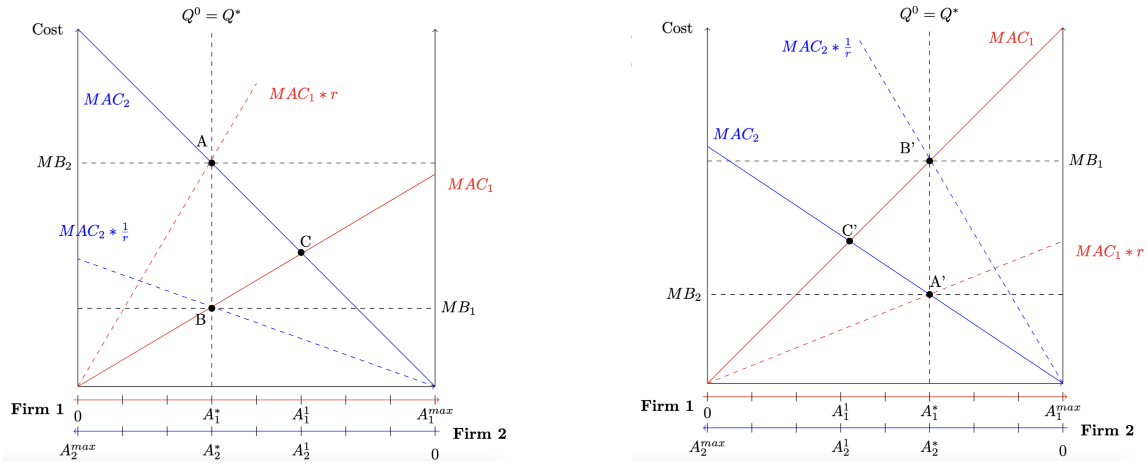
First, in the case of perfect information, I demonstrate how choices for the required abatement for a new sector and the trading ratio for this new sector will impact total social welfare. The choice of required abatement for this new sector $\bar{A}_2$ must reflect where its sector's marginal damages are equal to marginal costs. Similar to designing an autonomous cap-and-trade system, efficiency requires marginal costs to be equal to marginal damages in equilibrium. Secondly, given the differences in marginal damages in our model, a first-best solution requires the trading ratio r to be equal to the ratio of marginal damages ($r = \frac{\delta_2}{\delta_1}$).[9] This is analogous to findings from the literature in which CAT systems are being designed from scratch (Montgomery, 1972; Muller and Mendelsohn, 2009; Fowlie and Muller, 2019). Proof of this proposition can be found in Appendix A1.

Figure 1 graphically illustrates a scenario described above. In panel A, the existing sector 1 has a lower marginal cost of abatement and lower marginal benefits from abatement than the new sector. The red line represents the marginal abatement cost curve for the existing sector. The blue line represents the marginal abatement cost curve from the new sector. Dashed horizontal lines represent the marginal benefits from abatement from each sector, respectively. Graphically the vertical dashed line (Q^0) represents the initial quantity of abatement required by each sector. In panel B, the existing sector has relatively higher marginal costs and marginal benefits from abatement.

If the initial sector continued to operate independently, similar to a scenario of autarky, this sector would abate emissions equivalent to the required cap for their sector Q^0. The permit price for this sector would be equal to their marginal benefits of abatement. This is represented at points B and B' in Figure 1. Similarly, if the second sector were designed such that the required abatement for this sector would equate the marginal benefits and marginal costs of abatement from this sector ($\bar{A}_2 = \frac{\delta_2}{\gamma_2}$). Once linked, if regulators allowed permits to be traded across sectors using a trading ratio of 1, this would result in an inefficient equilibrium at points C or C' as sectors would equate their marginal costs, neglecting their marginal benefits curves. This equilibrium would result in

[9] This is equivalent to the more general case where the trading ratio is equal to the ratio of the marginal damages $r = \frac{D'(A_2)}{D'(A_1)}$.

Firm 1 completing A_1^1 units of abatement and Firm 2 completing A_2^1 units of abatement. However, this distribution of abatement would be sub-optimal. Marginal costs of abatement (A_1^1) would not be equal to marginal benefits of abatement from the first sector (MB_1). Similarly, the second sector would be sub-optimal as well. Therefore, regulators would need to set a trading ratio equivalent to the ratio of marginal benefits between sectors. Graphically, the dashed red and blue lines represent the opportunity cost of trading with the other sector at a trading ratio of r. This trading ratio ensurers no sector could decrease costs by purchasing permits from the other sector. Therefore, equilibrium abatement quantities will stay at A_1^* and A_2^*.



(a) $MC_1 < MC_2$ (b) $MC_1 > MC_2$

Figure 1: Using Optimal Trading Ratios and Abatement with Complete Information

Proposition 2 *If the new sector abatement requirement $\bar{A}_2$ and trading ratio r are set efficiently- as outlined in Proposition 1- no inter-sector trade will occur in the cap-and-trade system.*

Cap-and-trade systems are designed such that firms will trade based on abatement costs. However, when optimally extending the systems described above, the "trade" part of these systems will be moot. In practice, Proposition 2 signifies that incorporating a new sector is equivalent to not incorporating the new sector into an existing system and instead establishing a separate policy. In this scenario which sectors have differences in marginal benefits, any benefits of cost-reducing are offset by an increase in marginal benefits. Therefore, efficiently setting the trading ratio, incorporates the relative marginal benefits of abatement between sectors into the market. Figure 1 displays that no matter which sector has higher marginal costs, optimal policies for new abatement requirements and trading ratios will lead to an equilibrium abatement equivalent to one produced in autarky. Proof of Proposition 2 is in Appendix A2.

Although theoretically, incorporating a new sector with the optimal required abatement and trading ratio is equivalent to establishing an independent system for the new sector; there may be other potential political or economic costs of doing so. These costs may come from administrative or bureaucratic costs to design or develop a new system. Other difficulties may come from political challenges to establish a new system. Extending existing policies may be more politically feasible than starting anew.

3.1 Inefficient Existing Markets

So far, I have analyzed extending cap-and-trade regulations when the existing market sector is operating efficiently. Now this analysis shifts focus to a scenario in which the existing market sector is operating inefficiently. There are a multitude of cases in which the initial markets may be operating inefficiently. In order for the market to be operating efficiently the permit price of a tonne of CO_2e in the market should be equal to the marginal damages caused by a tonne of emissions. For example, the EU ETS permit price has regularly been considered on the lower side of possible estimates for the social cost of carbon. This would suggest the existing market as a whole is operating inefficiently. This leads to the question of how should a regulator choose to incorporate the new sector. What would be the best choices for $\bar{A}_2$ and r in terms of efficiency of the whole system when the initial sector is operating inefficiently?

Proposition 3 *Under perfect information, if the initial sector is operating inefficiently such that* $A_1 \neq \frac{\delta_1}{\gamma_1}$*: choices for required abatement* $\bar{A}_2$ *and the trading ratio* r *can be made such that the first-best allocation is recovered. Required abatement for the new sector should be set at* $\bar{A}_2 = \frac{1}{r}(\frac{\delta_1}{\gamma_1} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}$ *and* r *should be at* $r = \frac{\delta_2}{\delta_1}$.

The initial sector could be suboptimal in two ways. First, the equilibrium marginal costs could be above the marginal damages. This is equivalent to a cap being set too strict. This imposes firms to complete abatement which is more costly to the firm than beneficial to the environment. In this scenario, new sector abatement requirements could help loosen the cap on the initial sector. Second, the initial sector's marginal costs could be below the marginal damages from that sector. This would mean the initial cap was set to loose. The new sector cap could be used to effectively tighten the cap on the initial sector, raising marginal costs to be in line with marginal damages from emissions.

Figure 2 graphically represents this scenario. Staring at a quantity of permits $\bar{A}_1$ and $\bar{A}_2$, the social planner would prefer sector 1 to perform less abatement while having sector 2 perform more abatement. The red and blue dashed lines represent the opportunity cost of trading with the other sector. As the initial permits have already been distributed, willingness to trade with the other sector is relative to the marginal abatement cost at this initial quantity $\bar{A}_1$ and $\bar{A}_2$ and the trading ratio. Therefore, the opportunity cost line for Firm 2 to purchase permits from Firm 1 can be represented as $r((A_1 - \bar{A}_1) + MAC(\bar{A}_1))$.

If the initial sector is operating inefficiently, the regulator can make optimal choices of $\bar{A}_2$ and r such that the whole system will readjust to operate efficiently. The green shaded area represents the increase in welfare from these choices compared to a system of autarky. Points A_1 and A_2 represent where marginal costs for abatement in their representative sectors are equal to the marginal benefits from abatement in their sector.

Corollary 1 demonstrates that when regulators are choosing to extend an inefficient market, the choice for $\bar{A}_2$ should differ from the cap chosen when designing systems from scratch.

Corollary 1 *Selecting the optimal* $\bar{A}_2$ *when extending an inefficient system differs from designing a system from scratch. If marginal damages differ between sectors and the first sector is set inefficiently, setting a new abatement cap equal to* $\bar{A}_2 = \frac{1}{r}(\frac{\delta_1}{\gamma_1} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}$ *is more efficient than setting a overall cap equal to* $\bar{A}_2 = \frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\gamma_2} - \bar{A}_1$ *when using an optimal trading ratio equal to* $r = \frac{\delta_2}{\delta_1}$.

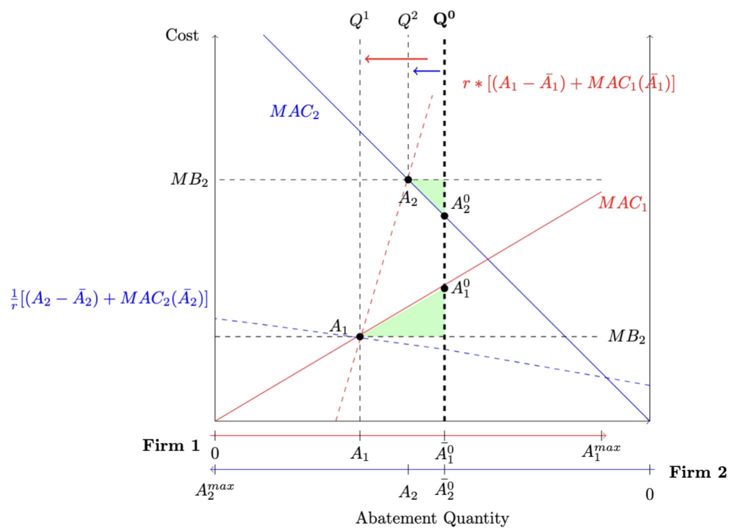


Figure 2: Using Optimal Trading Ratios and Abatement with Complete Information When Initial Sector Inefficient

Intuitively, the optimal choice for $\bar{A}_2$ should not be the same as when the first sector is operating efficiently. This is because if the first sector is operating inefficiently, the quantity of permits they are over or under their optimal abatement need to be traded to the second sector. However, with a trading ratio not equal to one, these permits are not equal to one permit in the second sector. Therefore, the first term of $\bar{A}_2$ adjusts the optimal choice for the second sector based on the magnitude of the inefficiency in the first sector and the trading ratio. Using these choices our total welfare function will be first-best. If the first sector is operating efficiently, or the marginal damages are equal, this function simplifies to $\bar{A}_2 = \frac{\delta_2}{\gamma_2}$ such as in Proposition 1. Proof of Proposition 3 and Corollary 1 are shown in Appendix A3.

These results have two main implications. First, if the new abatement requirement is set similar to what would have been chosen in Proposition 1, the market would fail to reach the first-best solution. This is because the second sector needs to incorporate information from the first sector's inefficiencies and their trading ratio. Second, with complete information on marginal benefits and costs, in order to achieve an efficient expansion of a cap-and-trade system with differential marginal benefits, optimal trading ratios should be set at the ratio of these marginal benefits. The optimal trading ratio only depends on marginal co-benefits between sectors, while the optimal new abatement cap depends on the trading ratio. Therefore the trading ratio is necessary to know before the new abatement requirement can be set.

3.2 Restrictions on Trading Ratio or Required Abatement

Often there may be political obstacles that may limit a regulator's choice for the trading ratio or the new abatement cap. A common restriction could require regulators to use a trading ratio equal to one. This ensures every sector's emissions are equivalent and no political favoritism could be perceived between sectors. Alternative trading ratios may be prone to lobbying or legal battles which may be more burdensome than beneficial. Other restrictions may limit a regulator's choice for the new sectors required abatement by requiring regulators to grandfather this new sector a portion of their historical emissions. Next, this paper examines the question, if there are constraints on one of these choice variables, could regulators still achieve first-best solutions?

Other researchers have shown that in CAT systems with differential marginal damages, setting a trading ratio equal to 1 is inefficient (Holland and Yates, 2015; Fowlie and Muller, 2019). These papers have started from a framework of designing the system from scratch where regulators can optimally choose the required abatement from the entire system. Then, knowing how large the system will be and the marginal damages of different sectors, they can choose optimal trading ratios. However, none of these papers have shown if the initial sector is operating inefficiently, could choosing a trading ratio equal to one ever be the optimal policy?

Proposition 4 *Under perfect information, if sectors have different marginal damages, no choice for required abatement from the new sector $\bar{A}_2$ will achieve a first-best solution if the trading ratio is set to 1.*

In Proposition 3, I demonstrate the optimal choice of both the trading ratio (r) and required abatement ($\bar{A}_2$) when the first sector is operating ineffiecently. The optimal choice for the trading ratio ($r = \frac{\delta_2}{\delta_1}$) should never be equal to one when sectors have different marginal damages. Proposition 4 demonstrates that no choice of $\bar{A}_2$ could adjust the inefficient system to a first-best solution when the trading ratio is constrained to one. Proof of Proposition 4 is in Appendix A4.

On the other hand, what if the regulators were required to select a set abatement quantity for the new sector? It is possible the regulators would want to choose a required abatement from the new sector equal to a portion of their historical emissions or to where sectoral marginal damages equal sectoral marginal costs ($\bar{A}_2 = \frac{\delta_2}{\gamma_2}$). Proposition 5 shows that if a regulator is required to set the new sector abatement at that level, no choice of a trading ratio could be used to achieve a first-best solution.

Proposition 5 *Under perfect information, if the initial cap is inefficient and sectors have different marginal damages, no choice for trading ratio (r) will achieve a first-best solution if the new sectors abatement requirement is set equal to* ($\bar{A}_2 = \frac{\delta_2}{\gamma_2}$).

Proof of Proposition 5 is in Appendix A5. Similarly to Proposition 4, I demonstrate that both policy parameters are crucial for readjusting a cap-and-trade system to the first-best efficient solution. The most common technique used by CAT systems is to begin by grandfathering in existing first by giving them a certain percentage of their historical emissions. Then, over time, this allocation of permits is reduced. It is unlikely that these choices of percent of historical emissions would be economically efficient and, therefore, would be extremely difficult be able to achieve a first-best solution with any possible trading ratio.

3.3 Restructuring the Initial Sector

Previously this paper demonstrates the importance of using both a trading ratio and a new emissions cap when extending an inefficient system to a new sector. A fundamental assumption of this model is that it assumes there can be no change to the abatement requirement for the existing sector when integrating a new sector. In policy examples, such as the EU expansion to aviation, there are reasons why the existing sector abatement would not be as easily manipulated compared to the new sector. This may be because of potential international agreements or targets the region has pledged to meet for specific sectors. Often it is the case that permit allocation schedules are set years in advance and have large political costs to manipulate. However, in other scenarios, it may be simpler to adjust the amount of permits given to the initial sector. In these circumstances, adding permits to the initial sector can have the same impact as adding them to the new sector, if the trading ratio is accounted for.

Corollary 2 *Under perfect information, the efficiency of linking a cap-and-trade system to a new sector can be achieved by switching the initial allocation of permits between sectors if regulators account for the trading ratio.*

If it is possible to manipulate $\bar{A}_1$ alongside $\bar{A}_2$, then the optimal choice for $\bar{A}_1$ and $\bar{A}_2$ should be equal to a total abatement required by the system.

$$\bar{A}_2 + \frac{1}{r}\bar{A}_1 = \frac{\delta_2}{\gamma_2} + \frac{1}{r}(\frac{\delta_1}{\gamma_1}) \tag{10}$$

Achieving this could be done by adding additional required abatement to the existing sector ($\bar{A}_1$), or changing the amount of abatement done from the new sector ($\bar{A}_2$). However, if the initial system could manipulate its required abatement on its own, this poses another question of why the initial system was operating inefficiently in the first place. Why would they not adjust their own cap to become more efficient? There must be some barrier prohibiting these markets from freely adjusting their own cap. Potentially, adding a new sector could create a circumstance where decisions could be made regarding the overall cap. Since they are already manipulating the program by linking it to a new sector, this may also be a time to change the overall cap of an existing system.

3.4 Prices vs Quantities Debate

What policy intervention should be used to control global greenhouse gas emissions like CO_2? This debate has been a long-standing issue in environmental economics. Pigou (1920) introduced the concept of pricing externalities such as pollution through a tax. Dales (1968) introduced the idea of creating property rights in the form of tradable pollution permits as an alternative to Pigouvian taxes. Then, Montgomery (1974) proved the formal equivalence between a price on pollution and a quantity representing the total allotment of tradable permits. Thereafter, economists widely accepted the equivalence between pigouvian taxes on pollution and an allotment of permits in a cap-and-trade system which results in the same competitive equilibrium market price as the tax.

In this model, I consider only the possibility of regulating this new sector by adding it to the existing cap-and-trade system. As many other researchers have shown, it is possible to have multiple policy instruments co-existing at the same time (Mandell, 2008). This is a common problem faced by real-world policymakers. Often, there may be large non-pecuniary or bureaucratic costs for beginning a new program. It is plausible to think of a policy environment where regulators may opt to design an alternative program for this new sector. There are a plethora of economic arguments for why this may be more efficient than the extension scenario. In theory, it could be possible to set Pigouvian-style taxes on all pollutants and locations individually. Effectively eliminating the need to incorporate heterogeneous co-pollutants in cap-and-trade systems for GHGs. Economically it would be efficient, however, feasibly it would be extremely tedious. A policy could set a tax of $40 on a ton of particulate matter from a factor in rural Texas, while setting a tax of $400 on a ton of SO_2 from a power plant in California. As shown in Muller and Mendelsohn (2007), these pollutants could be taxed according to their individual marginal damages based on the type of pollutant and the geographic area that the pollutant affects. However, differentiating between more than a thousand point and non-point polluters in the U.S. or EU alone would be infeasible.

Another argument for choosing to regulate a sector with different marginal damages separately from an existing emissions trading system could come from uncertainty. Weitzman's fundamental result demonstrates that with uncertainty in marginal costs and marginal damages, price-based instruments (taxes) will outperform quantity-based instruments if the slope of the marginal cost curve is greater than the slope of the marginal damage curve (Weitzman, 1974). In my model, I assume linear marginal damage curves such that each ton of pollution creates the same marginal damage on the region. Because of this flat marginal damages curve, with our positively sloped marginal cost curve a price style instrument would be more effective in regulating this new sector relative to incorporating it into the quantity based cap-and-trade regulation.

This poses a strong argument to consider outside policy instruments as possible ways to regulate pollution from this new industry. However, if the initial market is operating inefficiently, incorporating a new sector may be beneficial in helping correct this inefficiency and generate even larger gains compared to if regulators were to create a price-based regulation for the new sector. Utilizing a Pigouvian tax on pollutants in the new industry would fail to help the inefficiency of the existing cap-and-trade market.

4 Simulation Model of EU ETS Aviation Expansion

In the previous section, I develop a theoretical model to demonstrate how trading ratios and new abatement requirements are important choices for regulators when incorporating new sectors into cap-and-trade systems. Both of these choices are extremely important for the economic efficiency of the system and manipulation of either choice will affect total abatement, total costs, and the distribution of welfare within these systems. In this section, I connect this theoretical model with concrete policy choices within an emissions trading system. Using this theoretical framework, I simulate the EU ETS decision to incorporate the aviation sector into their cap-and-trade system. This is one of many examples of an existing cap-and-trade system that desires to expand to a new sector through linkage. My theoretical model provides an excellent framework to study the efficiency of linking these environmental regulations.

4.1 The European Union Emissions Trading System (EU ETS) and Aviation

In 2005, the European Union began the world's largest carbon cap-and-trade system. This system has developed as an archetype for other regions around the globe, advancing climate policies. Currently, it regulates over 10,000 installations encompassing over 1,400 Million tonnes of CO_2 equivalent emissions ($MtCO_2e$) from electricity generation and other industrial activities (European Commission, 2024). Although regulating billions of emissions each year, the EU ETS only covered about 40-45% of total EU greenhouse gas emissions.

Over time, this system has grown through many phases and policy changes. In 2008, the European Parliament and the Council adopted a new law, namely *Directive (2008)/101/EC*, amending the EU ETS to include aviation activities in 2012 (Council of the European Union, 2009). This was the first major sectoral addition to an international cap-and-trade system. Through a highly debated process, only flights within the EU were eventually required to submit permits for their emissions. Aviation emissions make up around 3.5% of worldwide anthropogenic emissions while comprising about 8% of all EU ETS regulated emissions (Schmalensee and Stavins, 2017).

One challenge of adding aviation to the EU ETS was to address the existing EU climate targets and commitments. Desiring to reach their emissions reduction targets outlined in the Kyoto protocol, the EU was concerned about linking the aviation sector to their existing cap-and-trade market.

Aviation emissions were not considered in these climate targets. Due to this fact, regulators were apprehensive that emissions reductions in aviation would supplant emissions reductions in other sectors, which were a part of their climate commitments, therefore making it more difficult to achieve their commitments. In order to ensure these spillovers would not occur, aviation emissions were included in the EU ETS through a unique unilateral linkage. Firms in other industries besides aviation were required to cover their emissions by surrendering general EU allowances (EUA). While, aviation firms were given their own set of permits EU Aviation Allowances (EUAA). Aviation firms were allowed to buy EUA permits from other sectors to cover their emissions; however, they could not sell their EUAAs to non-aviation firms. This was done to ensure the meeting of emissions targets for other sectors within the EU ETS, while also allowing benefits from trade between aviation and existing sectors.

My theoretical model outlines two potential policy parameters that regulators can manipulate during the linkage of cap-and-trade systems. These regulators have choices over the required abatement for this new sector and the trading ratio between the new and existing sectors. In 2012, the EU made choices for both of these variables when incorporating aviation. First, they chose the permit allocation for the new sector. Aviation firms were given permits equivalent to 95 percent of the sector's average 2004-2006 emissions. Given the average emissions of airlines from 2004-2006, airlines were allocated about 38 million permits. Of these permits, 82% were freely allocated, 15% were auctioned, and the remaining 3% were made available for new entrants.[10] Given this allocation, the aviation sector was required to abate around 2 million tons of CO_2 emission from their business as usual practices. This was their choice for $\bar{A}_2$ in our theoretical model. Emissions allowances were slated to fall by 1.4% each year beginning in 2012. Next, regulators determined a trading ratio between sectors. Traditionally, linked sectors or systems have been linked with a trading ratio equal to 1. Consistent with other linkages and the understanding of uniformly mixed pollutants, EU regulators choose to link the new sector using a trading ratio of 1, however, only unidirectionally.[11] Regulators failed to consider any differences in marginal co-benefits of abatement between aviation and other sectors.

Two unique factors make this cap-and-trade expansion a perfect setting to study using my

[10] Freely allocated permits were distributed based on a benchmark of 0.6422 emissions allowances per 1000 ton kilometers flown

[11] This unidirectional restriction was lifted in 2021 such that stationary sources may also submit EUAAs (European Commission, 2020).

theoretical model. First, although aviation does not make up a significant share of global emissions, it is one of the most challenging sectors to decarbonize. Due to high fixed costs in developing and maintaining an air fleet and minimal alternative fuel sources, it is not easy to reduce emissions from aviation. In recent years, some progress has been made to improve the efficiency of fuels; however, it is an arduous process. Because of these challenges, the aviation industry faces a relatively high marginal abatement cost curve. With a relatively high marginal abatement cost and a growing industry, we would expect aviation to be a net purchaser of EUA's in the market (Tang and Hu, 2019). Gains from linking cap-and-trade systems come from firms having different marginal abatement cost curves. Combining other sectors with the aviation sector, which we expect to have a relatively high marginal abatement cost curve, opens up a variety of possibilities for reducing the costs of emission regulations through trade.

Second, marginal benefits from abatement of CO_2 are vastly different between aviation and other stationary sectors. In this section, these benefits of abatement are synonymous with avoiding future damages from those emissions. There are two major reasons for this discrepancy in the quantity of avoided future damages per unit of CO_2. First, aviation pollutants emitted at different altitudes have vastly different global warming potential (GWP) than pollutants emitted on the ground. Based on weather conditions and altitude, aviation emissions can contribute to the formation of contrails and contrail cirrus. These emissions have their own GWP.[12] Second, aircraft operations produce a variety of co-pollutants including NO_x, SO_x, particulate matter, water vapor, and aerosols. Many of these emissions not only contribute to contrail formation but can also cause extremely harmful local damage to health and ecosystems. These co-pollutant concentrations vary compared to stationary sources in the EU ETS. Due to this heterogeneity, abatement of aviation CO_2 emissions could result in a larger reduction of global damages compared to other stationary sources in the EU ETS. Understanding the differences between damages from aviation and other EU ETS sources is critical for regulators and economists to properly link this new sector into the existing cap-and-trade system.

Although this policy was set to take place in 2012, I use the year 2015 to simulate our model, as that was the first year after the "stop the clock" fight was concluded and the regulation officially became binding.[13] Everything will be calculated in terms of 2015 euros.

[12] Lee et al. 2009, estimates that in 2005 the anthropogenic radiative forcing of non-CO_2 emissions accounted for 3.3% of GWP compared to the 1.6% from aircraft induced CO_2.

[13] The "stop the clock" phase refers to the decision to pause the EU ETS regulations to facilitate negotiations with

4.2 Estimating Marginal Costs

In order to simulate the welfare impacts of the integration of aviation into the EU ETS, I quantify the parameters from my theoretical model. The first step is to estimate marginal abatement cost (MAC) curves. The marginal abatement cost curves define how firms will optimize their own abatement decisions and the equilibrium permit price in the market.

Estimation of these marginal abatement cost curves has been done in countless economic studies from different sectors and regions around the globe (Kesicki and Strachan, 2011; Harmsen et al., 2019; Nordhaus, 1993). There are two popular ways to calculate these MAC curves: bottom-up and top-down approaches. A top-down approach typically uses a Computable General Equilibrium (CGE) model to analyze the whole economy and include spillovers and benefits from technological progress. Alternatively, bottom-up approaches use estimates from engineering or other scientists with real data on abatement costs and potential technologies capable of reducing emissions. For this paper, I will adapt both a top-down approach to MAC curves for estimating MAC for the EU ETS and a bottom-up approach for the aviation industry.

4.2.1 Marginal Abatement Cost of EU ETS

First, I begin by estimating the marginal abatement cost curve from the existing EU ETS. The EU ETS covers over 10,000 installations from a variety of different sectors. The traditional approach to estimate marginal abatement cost functions is to fit an aggregate curve using point estimates from bottom-up data. However, these bottom-up approaches can often be quite heterogeneous across different pollutants and sectors. For example, some chemical industries may have multiple substitutes and can easily reduce GHG emissions by switching to other products with much lower emissions. On the other hand, other industries may have very expensive abatement options where abatement options may have few substitutes or involve capital-intensive production processes. Therefore, to estimate MAC curves for the non-aviation industries of the EU ETS, I adopt top-down approaches from large integrated assessment models (IAM). I begin by using the standard quadratic abatement cost functions; however, I later perform sensitivity analysis with alternative functional forms of abatement costs with adapted abatement costs from Nordhaus' DICE and RICE integrated

International Civil Aviation Organization (ICAO) for a worldwide aviation emissions regulation.

assessment models and Landis (2015).[14]

Using MAC cost functions from EU, their MAC can be written in terms of millions of tonnes of CO_2 abatement as:

$$MAC_{ets} = 0.0375A^{*}_{ets}$$

.

Next, I take the top-down approach from the DICE and RICE models (Nordhaus, 1993; Barrage and Nordhaus, 2024). These models assume that the cost curves have the functional form of:

$$C(\mu(t)) = \theta_1(\mu(t))^{\theta_2} \tag{11}$$

θ_1 represents the abatement coefficient. θ_2 represents the exponent of the control cost function.$\mu(t)$ is the emissions control rate or, alternatively, the required abatement percentage at time t. I construct our costs assuming an emissions control rate of 5% in 2012. My model analyses emissions reductions by millions of tonnes of abatement rather than a percentage. Therefore this 5% reduction in emissions is equivalent to 200 $MtCO_2$ of abatement. Often these cost functions are assumed to be quadratic ($\theta_2 = 2$). However, the recent additions of the DICE models use a higher θ_2 ($\theta_2 = 2.6$). [15] Differentiating this abatement cost function, the marginal abatement cost curve from these top-down approaches can be translated into our theoretical framework where ($MAC = \theta_1\theta_2(\mu(t))^{\theta_2-1}$). I convert this formula such that instead of $C(A)$ representing the percentage of GDP needed to reduce emissions by a certain percent μ, $C(A)$ represents a monetary value of euros required to abate A^* million tonnes of CO_2 ($\gamma_1(A^*)^{\theta_2-1}$). A^* is the equivalent of emissions control rate in terms of millions of tonnes of CO_2 abatement. In Appendix A7, we perform sensitivity analysis of our model with alternative choices of γ_1 and θ_2.

Doing this simulation ex-post, allows us the ability to compare our estimates from our top-down marginal abatement cost curves to the market permit price during 2015. In 2015, the average market price for a EUA permit was around €7.60 (European Commission, 2015). Estimates from

[14] There have been many iterations of the DICE (1993) and RICE (1996) models, this paper utilizes the most recent versions.

[15] The Nordhaus DICE model estimates θ_1 as the fraction of output that is required to reduce emissions. Their estimates of θ_1 are around 0.109. This represents that in order to cut emissions by μ percent, it will cost around 11% of output. This equation calculates their costs in terms of a percentage of total output. I convert this formula such that θ_1 is not a percentage of output but a euro amount per million tons of abatement in 2012. This $\theta_1 = 0.000657$ making $\gamma_1 = 2.6 * 0.000657 \approx 0.017$. Using these parameters permit price in the EU ETS in 2012 would be around €8.17.

our quadratic abatement cost curves result in a very similar permit price of around €7, while estimates from the DICE abatement cost curve result in a permit price of around €8 per tonne of CO_2. Both of these methodologies estimate prices that are relatively close to the actual price of permits in 2015.

4.2.2 Marginal Cost of Aviation Abatement

Most of these top-down MAC curves fail to include the aviation sector. Therefore, to estimate marginal abatement costs of the aviation sector, I use reports written by transportation agencies throughout Europe. These reports are similar to step-wise bottom-up MAC curve estimates. I first take estimates of MAC from the UK Transportation Sector (Holland et al., 2011). This report provides estimates of the costs of abatement in 2012 for the aviation sector of the UK. Assuming the European airline industry is similar to that of the UK, I extrapolate aviation MAC curves for the rest of the EU. Similar to the abatement cost curves from the EU ETS, abatement is modeled in terms of percent reduction in BAU emissions instead of total tonnes of abatement. The aviation industries required emissions control rate was 5% or equivalent to 2 million tCO_2 of abatement (Schmalensee and Stavins, 2017).

This report finds that aviation abatement costs have a variety of potential low or even negative solutions. Their models show that large decreases in emission could come from better usage of aircraft capacity or optimizing landing and take-off practices. However in my model, I assume that these cost-saving actions have either been already taken into account by airlines, or there are alternative constraints, by air traffic control or airports that would not allow firms to reduce emissions substantially through these methods.[16] On the other hand, their marginal abatement costs come from some more costly procedures such as airplane retirements. To reduce 5% of their emissions this paper estimates 4.1% of that can come from replacing the oldest and least efficient aircraft. This would cost on average a £118 per tCO_2. Compared to prices in the EU ETS for permits (around €7), it would be understandable for airlines to purchase permits from the market instead of paying the price to do their own abatement. Continuing along the MAC curve for aviation, the next 5% of emissions reductions would come at a cost of £434 per tCO_2. These MACs are extremely high relative to other sectors of the EU ETS. Using these estimates for marginal

[16] This model shows the potential for over 23% of aviation emissions to be abated at a negative cost. If accurate, this abatement potential would lead aviation firms to be net sellers of permits. However, in practice, aviation firms bought around 18 million permits per year from other EU ETS sectors

abatement costs at different quantities, the functional form of the MAC for aviation is:

$$MAC_{aviation} = 61 * A_{aviation}$$

The slope parameter of our MAC curve uses a γ_2 of €61 per million tonnes of abatement.[17] These marginal abatement cost estimates are three orders of magnitude larger than the estimates from other EU ETS sectors. In practice, these estimates are consistent with the aviation sector buying millions of permits from other EU ETS sectors. However, ex-post data on the number of permits purchased and surrendered by each sector does not shed any light on just how high these marginal abatement costs are for aviation. [18] In the Appendix, we include a sensitivity analysis of alternative choices of γ_2 and functional forms for aviation.

4.3 Estimating Marginal Benefits of Abatement

Now, I focus on understanding heterogeneity among marginal benefits of abatement from different emissions sources. Due to the nature of climate change, these benefits of abatement are manifested through avoided future damages of emissions. To properly estimate how to incorporate aviation into the EU ETS, we first need to understand the marginal damages from the existing sectors within the cap-and-trade system and the marginal damages from the aviation sector. In this model, I assume that marginal damages from these emissions are constant. Because these sectoral emissions make up less than 10% of GHG emissions around the world, I assume that at this point on the marginal damages curve, damages are relatively constant.

To compare the heterogeneous damages from aviation and other stationary sources, I include only the damages from the net radiative forces or global warming potential of these emissions. In stationary sources of the EU ETS, these include only carbon dioxide emissions. For the aviation sector, these radiative forces come from carbon dioxide (CO2) along with nitrogen oxides (NOx), water vapor, soot and sulfate aerosols, and increased cloudiness due to contrail formation.

[17] We translate our estimates into 2015 dollars and get around €122 per tonne of CO_2

[18] Aviation firms' cost minimization would result in this number of permits purchased whether marginal abatement costs are $\gamma_2 > 3.5$.

4.3.1 Marginal Benefits of Abatement from the EU ETS

Quantifying the avoided future damages from greenhouse gas emissions may be one of the most common studies completed by environmental economists. The term "Social Cost of Carbon" (SCC) was originally established by the Reagan Administration of the U.S. in 1981. This value represents the present value cost of an additional ton of CO_2 emissions (Pearce, 2003). Over time different economists including Nordhaus (1993) and Stern (2006) have developed their own models to value the cost of one ton of greenhouse gas emissions (Anthoff et al., 2009; Tol, 2011; West et al., 2013; Nordhaus, 2017; Pindyck, 2019; Wang et al., 2019[19]). This metric is based on a complicated set of economic and ecological assumptions including the pure rate of time preference (PRTP), the value of statistical life, ecological tipping points, and uncertainty in future environmental and economic conditions.

As estimating the social cost of carbon, or the marginal benefits of carbon abatement, have been incredibly widely studied topics over the last few decades, unsurprisingly these estimates have changed over time. As environmental and economic modeling of the catastrophic impacts of climate change has grown over the last few decades, our estimates for the social cost of carbon have also grown. Therefore, it may be more realistic to model policymaker's decisions from the state of information they had in 2012. At the time, the social cost of carbon estimates from economists and policymakers around the world was much lower than what they currently are in 2024. The United States Interagency Working Group on Social Cost of Carbon (2010) estimated the social cost of carbon to be $21 in 2010. Converting these estimates, the social cost of carbon should be around €16.60 in 2012 euros.

As a sensitivity analysis, I also use the estimates of the social cost of pollutants from recent papers in Europe and the United States and translate them into 2015 dollars. Wang et al. (2019) complete a meta-analysis on estimates of the SCC and obtain an average estimate of around $200 per ton of carbon. The German Environmental Agency released an assessment of the environmental costs of GHG emissions in which the social cost of carbon was estimated at €180 per tonne of CO_2 in 2019 Matthey and Bünger, Matthey and Bünger. Averaging these estimates, my sensitivity analysis uses an estimate of €175 per tonne of CO_2 in 2015.

[19]There are just a handful of economic and environmental studies developing and evaluating the social cost of carbon estimates.

4.3.2 Marginal Benefits of Abatement from Aviation

Quantifying damages from aviation poses a variety of challenges compared to estimates of other CO_2 emissions. A large literature has studied the warming potential of aviation emissions (Lee et al., 2009); Lee et al., 2021). Aviation fuel produces a variety of emissions, notably CO_2, NO_x, SO_x, hydrocarbons (HC), CO, particulate matter (PM), soot, water vapor, and indirect effects such as aviation-induced cloudiness (AIC). Unlike other sources, aviation emissions are emitted across a wide range of geographic areas and altitudes. The location and altitude of these emissions change their net radiative forcing.

Aviation-induced cloudiness and contrails have a unique GWP compared to other sources of emissions. Emissions of pollutants and water vapor in the atmosphere, including CO_2 and non-CO_2 emissions, have an overall warming impact. These contrails can have both positive and negative radiative forcing effects (RF); however, scientific consensus puts overall non-CO_2 effects of aviation as having a net warming impact (Lee et al., 2009). Lee et al. (2021) estimates the warming effects of non-CO_2 aviation emissions comprise about 66% of the net radiative forcing of total aviation emissions (Lee et al., 2021).

Therefore, in this model, we estimate that the radiative forcing of aviation emissions is 3x as large as the radiative forcing of emissions from a stationary firm in the EU ETS. If we assume the social cost of carbon accurately encapsulates the net present cost of the radiative forcing from these emissions, marginal benefits from abatement in the aviation sector are three times the social cost of carbon. In Appendix A7, we perform some sensitivity analysis on the ratio of aviation damages to other stationary sources in the EU.

4.4 Results

Table 1 displays the parameter estimates used in the simulation. Using these parameter estimates, I simulate welfare implications for a variety of potential policy choices when the EU ETS was linked to the aviation sector. Column 4 of Table 1 displays the main parameter estimates we use in our model. Due to economic or mathematical assumptions of our model or possible uncertainty, these estimates may range based on which sector or time period they were estimated on. Sensitivity analysis of these parameters is performed in the Appendix. Estimates for the required abatement from the EU ETS as a whole and the aviation sector are based on BAU emission from the EU ETS

Table 1: Parameter Estimates

Parameter	Units	Notation	Estimate	Source
Marginal Abatement Cost Parameter EU ETS	$\frac{€}{MtCO_2}$	γ_1	0.035	(DICE, 2019; Landis, 2015)
Marginal Abatement Cost Parameter Aviation	$\frac{€}{MtCO_2}$	γ_2	61	(UK Transport, 2010)
Marginal Damages EU ETS	$\frac{€}{tCO_2}$	δ_1	16.60	(Interagency Working Group, 2010)
Marginal Damages Aviation	$\frac{€}{tCO_2}$	δ_2	49.80	(Lee et al., 2021)
Required Abatement EU ETS	$MtCO_2$	$\bar{A}_1$	200	EU ETS Phase III
Required Abatement Aviation	$MtCO_2$	$\bar{A}_2$	2	EU ETS Phase III
Trading Ratio		r	1	EU ETS Phase III

Note: Parameter estimates are pulled from the most accurate analysis of marginal damages and marginal costs for the EU ETS and aviation sector would have known when this policy was implemented in 2012. Estimates are in terms of euros or millions of tonnes of CO_2. The top parameters refer to those which are exogenous parameters to the policymaker, while the bottom parameters (Required Abatement and Trading Ratio) are the policy choices.

Table 2: Results for Alternative Choices of Abatement Requirements and Trading Ratio

	A_e	A_a	p_e	p_a	TC	TB	Welfare	$\Delta\%$
Panel A: One-for-one								
$\bar{A}_a = 2$, $r = 1$	201.88	0.12	7.57	7.57	765	3,357	2,592	0%
Panel B: Marginal Benefit Trading Ratio								
$\bar{A}_a = 2$, $r = 3$	204.87	0.38	7.68	23.04	791	3,420	2,628	1.4%
Panel C: Extended Abatement Requirement and Optimal Ratio								
$\bar{A}_a = 10$, $r = 13.6$	301.94	2.53	11.32	154.61	1,905	5,138	3,233	24.7%
Panel D: Extended Abatement Requirement and One-for-One								
$\bar{A}_a = 10$, $r = 1$	209.88	0.12	7.87	7.87	826	3,490	2,664	2.7%

Note: Table 2 displays equilibrium abatement quantities (A), permit prices (p), total abatement costs (TC), Total avoided damages (TB), and percentage changes in welfare compared to the original policy choices (Panel A). Welfare is measured in millions of euros.

Phase III.

Table 2 describes the welfare and distributional impacts of four potential policy choices for this market. First, I examine the welfare impacts of the exact policy parameters chosen by EU regulators. These choices were the required abatement from the aviation sector (2 million tonnes of CO_2) and a trading ratio of 1. Given these parameters, the policy cost firms in the EU ETS a total of around 765 million euros to reduce their emissions. On the other hand, these reduced emissions avoided €3,357 million of future damages from these emissions. Next, Panel B describes the implications of choosing a trading ratio equal to the marginal damage ratio (r=3). If policymakers were able to slightly increase the trading ratio in order to incorporate the more beneficial co-benefits from abatement in the aviation sector, this policy choice would have slightly increased welfare by 0.3% compared to their original choices.

My theoretical model does not constrain the potential choices for either variable. However, in the simulation model, there may be some potential political limitations to either the required abatement for the aviation sector or the trading ratio. Panel C describes if regulators could have chosen to require more abatement from the new aviation sector. For example, I suppose they required aviation firms to reduce their emissions by 10 million tonnes ($\tilde{2}$5%). Then with this new quantity of required abatement, regulators could choose an optimal trading ratio. In this circumstance, the optimal choice of trading ratio would be equal to 13.6. A much larger ratio, but not as large as the ratio of marginal costs. Under these alternative choices, welfare of the system could have increased by 24.7%. As requiring 8 more million tonnes of abatement, both existing and new firms would bear the cost increase from €765 million to €1.9 billion. However, this choice of policy parameters would also lead to over 1.7 billion more in benefits from abatement of 102 million tons of CO_2 being abated. This additional abatement would lead to an overall welfare increase of around €640 million.

Finally, Panel D examines if regulators were required to keep the trading ratio equal to 1, but were allowed to increase the stringency on required abatement from the new sector. In this scenario, overall welfare increases by 3.9%. Compared to Panel A, the major difference between these two scenarios is that the existing sector does around 9 million more tonnes of abatement. Nearly all of the additional required abatement is completed by the existing sector, which has the lower marginal abatement costs. This comes from the new aviation sector purchasing the additional required abatement from the existing sector, and with a slightly higher demand, prices rise from

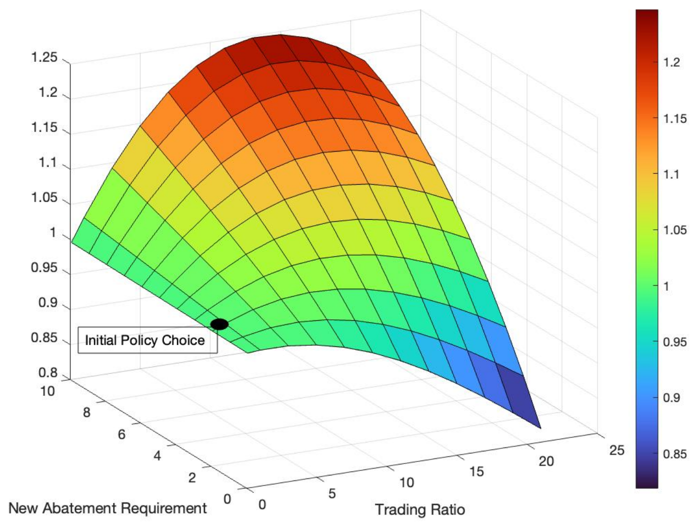


Figure 3: Welfare Heat Map By Choices for Trading Ratios and Abatement Requirements

€7.57 to €7.87. Figure 3 presents a graphic of welfare gains from alternative possible choices for both the trading ratio and abatement requirement. Manipulating either the trading ratio or the abatement requirement could lead to slight gains in welfare compared to the original policy choices. However, if both of these policy parameters were increased together, the system would see large welfare gains.

While alternative choices for trading ratios and new abatement requirements for the aviation sector would have substantially increased welfare, these policy choices would have imposed large costs on the aviation sector. Table 3 displays how alternative choices for the trading ratio and aviation sector required abatement would have impacted the distribution of costs and abatement across sectors. TC_e represents the total compliance cost after permits are bought or sold for the existing sectors of the EU ETS. TC_a represents the compliance costs for the aviation sector. In the case of Panels A and C, there is very little abatement occurring in the aviation sector ($A_a = 0.12$). This would require aviation firms to purchase permits from other sectors in the EU, lowering costs for the system overall. Imposing higher trading ratios between sectors would result in an increase in costs for the aviation sector. Similarly, imposing more abatement in the aviation sector would result in the aviation sector paying much more than originally designed. Imposing large costs on

Table 3: Distribution of Abatement Costs and Damages by Sector

	TC_e	TC_a	TB_e	TB_a	%ΔW
Panel A: One-for-one					
$\bar{A}_a = 2$, $r = 1$	749.6	14.7	3,351	6.0	0%
Panel B: Marginal Benefit Trading Ratio					
$\bar{A}_a = 2$, $r = 3$	749.4	41.7	3,401	18.9	1.4%
Panel C: Extended Abatement Requirement and Optimal Ratio					
$\bar{A}_a = 10$, $r = 13.6$	554.5	1350.2	5,012	126.0	24.7%
Panel D: Extended Abatement Requirement and One-for-one Trading					
$\bar{A}_a = 10$, $r = 1$	748.0	78.2	3,484	6.0	2.7%

Note: Welfare is measured in millions of euros. Abatement is measured in millions of tonnes of CO_2. Total costs are inclusive of the costs of buying permits from the other sector at the established permit price.

a specific sector is difficult to do politically, even if these costs would lead to large environmental benefits. Others in the literature have shown how these regulations could potentially lead to linkage or other competitive market effects that may reduce welfare (Nava et al., 2018).

5 Discussion

Environmental economists have modeled and analyzed cap-and-trade systems extensively over the past few decades. This paper builds on countless others to explore a new and increasingly frequent phenomenon of expanding cap-and-trade systems. These policies have been discussed over time, yet few researchers have modeled how policy choices will impact the efficiency of these linked. In 2022, there were 25 operational cap-and-trade systems throughout the globe, covering only 17% of global GHG emissions. Economists have shown these systems effectiveness in reaching environmental goals at lower costs compared to alternative command and control style policies. Because of this success, policymakers are now thinking about expanding these systems to cover more emissions through linkages to previously unregulated sectors. In this paper, I study the linkage of the EU ETS to the aviation sector in 2012. This framework could also be used by future policymakers to expand their existing ETSs to new sectors including: the EU expansion into maritime emissions in 2024, the US Regional Greenhouse Gas initiative plans to expand into transportation and other industries, and the China ETS linkage to include the cement, steel, and aluminum industries in 2024. This theoretical model provides an excellent framework to investigate these new policy choices and demonstrate some essential economic choices needed for optimally incorporating new sectors.

The EU ETS is the world's largest and longest-lasting cap-and-trade system. Because of this longevity, it was one of the first to increase the scope of its system by expanding to a new unregulated sector. Regulators made standard and safe choices for linking sectors. As observed in 2012, the EU ETS was linked to the aviation sector using a trading ratio of 1 and grandfathering aviation permits equivalent to around 95% of their historical emissions. In this paper, I show the limitations of these styles of choice and how they could be improved. Our simulation shows that because the permit price in the EU ETS was extremely low during Phase III of the policy, alternative policy choices for the trading ratio and required abatement could have improved the systems welfare. Failing to incorporate the vast differences in damages from aviation GHG emissions compared to other sectors was also another shortcoming of this policy. During these decisions in 2012, policymakers may have needed more accurate information on marginal costs or marginal benefits of abatement across sections. However, there could have been various political or alternative reasons for maintaining safe choices for these two policy instruments.

This paper opens the door to thinking about these policy parameters more efficiently, as well as some potential caveats and vital information to consider when making these large environmental policy decisions. One limitation of our model is understanding the marginal damages from aviation emissions. Although scientists have worked to quantify aviation emissions, understanding heterogeneity in contrail formation and human health impacts from aircraft emissions based on their flight paths and altitude is still difficult to quantify. Our estimates are based on the most accurate studies in 2024; however, this area of research continues to grow. Another limitation of our model is its static nature. The EU ETS and many other cap-and-trade systems are designed to tighten the cap over time, increasing the equilibrium price closer to marginal damages. A possible avenue for extension of this paper would be to investigate how the dynamics of each sector's emissions allocation would impact incorporating new sectors.

This paper discusses uncertainty in some scenarios of cap-and-trade policy making; however, I do not dive into the potential differences between carbon tax policies and cap-and-trade systems under this framework. The dense literature following Weitzman (1974) shows that this is a critical choice for designing environmental policies. There continues to be a large amount of uncertainty in the marginal abatement costs or damages of these pollutants, opening up a significant area of research to be developed in the future.

6 Conclusion

In this paper, I explore a policy framework that has become more common as environmental regulations grow around the globe. Extending cap-and-trade systems to new sectors through linkages creates unique policy choices where economics can play a pivotal role. When linking, policymakers have two important choice variables to manipulate: new emissions permit allocations and trading ratios. Historically, these decisions were built on cost-effectiveness without considering their impact on economic efficiency. This oversight could have been because of a desire to lessen the political burden of potentially controversial environmental policies. However, this paper demonstrates that optimal choices of both the new sectors permit allocation and trading ratio are crucial to integrate these new sectors efficiently.

This new theoretical model demonstrates how trading ratios and new abatement requirements will impact the efficiency of a cap-and-trade system when integrating a new sector. I demonstrate that with proper choices of a trading ratio and new abatement requirements, policymakers can achieve first-best allocations of cap-and-trade systems with heterogeneous co-benefits from abatement. However, when sectors have heterogeneous marginal benefits, constraints on either the trading ratio or new permit allocations will prevent a system from operating efficiently.

Utilizing this theoretical framework, this paper simulates the real-world policy of linking the aviation sector to the European Union Emissions Trading System in 2012. I show how alternative choices of trading ratios and new abatement requirements for aviation could have improved welfare by over €640 million annually. While small welfare benefits would have been captured by either increasing the trading ratio or increasing the required abatement from the aviation sector, utilizing both of these policy instruments together is crucial for large welfare gains. This paper analyses an increasingly more common policy decision surrounding international environmental regulations from a new perspective. As the threat of climate change becomes more dire and consequential, using economics to design environmental regulations can be highly effective in safeguarding our planet for future generations.

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7 Appendix

7.1 Appendix A1: Proof of Proposition 1

Given the required abatement for both sectors, firms will choose whether to meet their abatement requirements by doing their own abatement or buying permits from the other sector at a trading ratio of r. Firms minimize their costs such that:

$$\begin{aligned} min_{A_1,A_2}\ \frac{\gamma_1}{2}(A_1)^2 + \frac{\gamma_2}{2}(A_2)^2 - p_1(A_1 - \bar{A}_1) - p_2(A_2 - \bar{A}_2) \\ s.t.\ r(A_2 - \bar{A}_2) = \bar{A}_1 - A_1 \\ rp_1 = p_2 \end{aligned} \tag{12}$$

$$L = \ \frac{\gamma_1}{2}(A_1)^2 + \frac{\gamma_2}{2}(A_2)^2 - p_1(A_1 - \bar{A}_1) - p_2(A_2 - \bar{A}_2) + \lambda(\bar{A}_1 + r\bar{A}_2 - A_1 - rA_2) + \mu(rp_1 - p_2) \tag{13}$$

$$\begin{aligned} \frac{\partial L}{\partial A_1} = \gamma_1 A_1 - p_1 - \lambda = 0 \\ \frac{\partial L}{\partial A_2} = \gamma_2 A_2 - p_2 - r\lambda = 0 \\ \frac{\partial L}{\partial \lambda} = \bar{A}_1 + r\bar{A}_2 - A_1 - rA_2 = 0 \\ \frac{\partial L}{\partial \mu} = rp_1 - p_2 = 0 \end{aligned} \tag{14}$$

Substituting among first-order conditions, we get:

$$\begin{aligned} \gamma_1 A_1 - p_1 = \lambda \\ \frac{1}{r}(\gamma_2 A_2 - p_2) = \lambda \\ \rightarrow \gamma_1 A_1 - p_1 = \frac{1}{r}(\gamma_2 A_2 - p_2) \end{aligned} \tag{15}$$

Substitute in prices

$$\begin{aligned} r\gamma_1 A_1 - rp_1 = \gamma_2 A_2 - rp_1 \\ r\gamma_1 A_1 = \gamma_2 A_2 \\ A_1 = \frac{\gamma_2}{r\gamma_1} A_2 \\ A_2 = r\frac{\gamma_1}{\gamma_2} A_1 \end{aligned} \tag{16}$$

Now using the exchange rates

$$
\begin{aligned}
\bar{A}_1 + r\bar{A}_2 &= A_1 + rA_2 \\
\bar{A}_1 + r\bar{A}_2 &= A_1 + r^2\frac{\gamma_1}{\gamma_2}A_1 \\
\bar{A}_1 + r\bar{A}_2 &= A_1(1 + \frac{r^2\gamma_1}{\gamma_2}) \\
A_1 &= \frac{\bar{A}_1 + r\bar{A}_2}{1 + \frac{r^2\gamma_1}{\gamma_2}}
\end{aligned}
\tag{17}
$$

$$
\begin{aligned}
\bar{A}_1 + r\bar{A}_2 &= A_1 + rA_2 \\
\bar{A}_1 + r\bar{A}_2 &= \frac{\gamma_2}{r\gamma_1}A_2 + rA_2 \\
\bar{A}_1 + r\bar{A}_2 &= A_2(\frac{\gamma_2}{r\gamma_1} + r) \\
A_2 &= \frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1} + r}
\end{aligned}
\tag{18}
$$

Now we can write the regulators problem in terms of known parameters $\bar{A}_1$, γ_1, γ_2 and choice variables $\bar{A}_2$ and r.

$$
\begin{aligned}
\max_{\bar{A}_2, r} \quad TSW = \sum_i D_i(A_i) - \sum_i C_i(A_i) \\
= \delta_1(\frac{\bar{A}_1 + r\bar{A}_2}{1 + \frac{r^2\gamma_1}{\gamma_2}}) + \delta_2(\frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1} + r}) - \frac{\gamma_1}{2}(\frac{\bar{A}_1 + r\bar{A}_2}{1 + \frac{r^2\gamma_1}{\gamma_2}})^2 - \frac{\gamma_2}{2}(\frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1} + r})^2
\end{aligned}
\tag{19}
$$

I assume the first sector $\bar{A}_1$ is set optimally, such that $D_1'(A_1) = C_1'(A_1)$. Therefore when meeting all of their abatement requirements by themselves implying $\bar{A}_1 = A_1 = \frac{\delta_1}{\gamma_1}$

Now when optimizing this welfare function over all possible choices for $\bar{A}_2$ and r we arrive at choices of $\bar{A}_2 = \frac{\gamma_2}{\delta_2}$ and $r = \frac{\delta_2}{\delta_1}$. When plugging these results in our welfare function simplifies to the first-best solution.

$$
TSW^* = \frac{\delta_1^2\gamma_2 + \delta_2^2\gamma_1}{2\gamma_1\gamma_2} \tag{20}
$$

$$= \delta_1(\frac{\bar{A}_1 + r\bar{A}_2}{1+\frac{r^2\gamma_1}{\gamma_2}}) + \delta_2(\frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1}+r}) - \frac{\gamma_1}{2}(\frac{\bar{A}_1 + r\bar{A}_2}{1+\frac{r^2\gamma_1}{\gamma_2}})^2 - \frac{\gamma_2}{2}(\frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1}+r})^2$$

Plug in $\bar{A}_1$ and $\bar{A}_2$

$$= \delta_1(\frac{\frac{\delta_1}{\gamma_1} + r\frac{\delta_2}{\gamma_2}}{1+\frac{r^2\gamma_1}{\gamma_2}}) + \delta_2(\frac{\frac{\delta_1}{\gamma_1} + r\frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{r\gamma_1}+r}) - \frac{\gamma_1}{2}(\frac{\frac{\delta_1}{\gamma_1} + r\frac{\delta_2}{\gamma_2}}{1+\frac{r^2\gamma_1}{\gamma_2}})^2 - \frac{\gamma_2}{2}(\frac{\frac{\delta_1}{\gamma_1} + r\frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{r\gamma_1}+r})^2$$

Plug in r

$$= \delta_1(\frac{\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\delta_1}\frac{\delta_2}{\gamma_2}}{1+\frac{\frac{\delta_2}{\delta_1}^2\gamma_1}{\gamma_2}}) + \delta_2(\frac{\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\delta_1}\frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{\frac{\delta_2}{\delta_1}\gamma_1}+\frac{\delta_2}{\delta_1}}) - \frac{\gamma_1}{2}(\frac{\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\delta_1}\frac{\delta_2}{\gamma_2}}{1+\frac{\frac{\delta_2}{\delta_1}^2\gamma_1}{\gamma_2}})^2 - \frac{\gamma_2}{2}(\frac{\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\delta_1}\frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{\frac{\delta_2}{\delta_1}\gamma_1}+\frac{\delta_2}{\delta_1}})^2$$

$$= \delta_1(\frac{\frac{\delta_1}{\gamma_1}(1+\frac{\delta_2^2}{\delta_1\gamma_2}*\frac{\gamma_1}{\delta_1})}{1+\frac{(\frac{\delta_2}{\delta_1})^2\gamma_1}{\gamma_2}}) + \delta_2(\frac{\frac{\delta_1^2\gamma_2\delta_2+\delta_2^3\gamma_1}{\gamma_1\delta_1\gamma_2\delta_2}}{\frac{\gamma_2^2\delta_1^2+\delta_2^2\gamma_1\gamma_2}{\gamma_1\delta_1\gamma_2\delta_2}}) - \frac{\gamma_1}{2}(\frac{\frac{\delta_1}{\gamma_1}(1+\frac{\delta_2^2}{\delta_1\gamma_2}*\frac{\gamma_1}{\delta_1})}{1+\frac{(\frac{\delta_2}{\delta_1})^2\gamma_1}{\gamma_2}})^2 - \frac{\gamma_2}{2}(\frac{\frac{\delta_1^2\gamma_2\delta_2+\delta_2^3\gamma_1}{\gamma_1\delta_1\gamma_2\delta_2}}{\frac{\gamma_2^2\delta_1^2+\delta_2^2\gamma_1\gamma_2}{\gamma_1\delta_1\gamma_2\delta_2}})^2$$

$$= \delta_1(\frac{\delta_1}{\gamma_1} * \frac{1+\frac{\delta_2^2\gamma_1}{\gamma_2\delta_1^2}}{1+\frac{\delta_2^2\gamma_1}{\gamma_2\delta_1^2}}) + \delta_2(\frac{\delta_1^2\gamma_2\delta_2 + \delta_2^3\gamma_1}{\gamma_2^2\delta_1^2+\delta_2^2\gamma_1\gamma_2}) - \frac{\gamma_1}{2}(\frac{\delta_1}{\gamma_1} * \frac{1+\frac{\delta_2^2\gamma_1}{\gamma_2\delta_1^2}}{1+\frac{\delta_2^2\gamma_1}{\gamma_2\delta_1^2}})^2 - \frac{\gamma_2}{2}(\frac{\delta_1^2\gamma_2\delta_2 + \delta_2^3\gamma_1}{\gamma_2^2\delta_1^2+\delta_2^2\gamma_1\gamma_2})^2$$

$$\delta_1(\frac{\delta_1}{\gamma_1} * \frac{1+\frac{\delta_2^2\gamma_1}{\gamma_2\delta_1^2}}{1+\frac{\delta_2^2\gamma_1}{\gamma_2\delta_1^2}}) + \delta_2(\frac{\delta_2(\delta_1^2\gamma_2 + \delta_2^2\gamma_1)}{\gamma_2(\delta_1^2\gamma_2+\delta_2^2\gamma_1)}) - \frac{\gamma_1}{2}(\frac{\delta_1}{\gamma_1} * \frac{1+\frac{\delta_2^2\gamma_1}{\gamma_2\delta_1^2}}{1+\frac{\delta_2^2\gamma_1}{\gamma_2\delta_1^2}})^2 - \frac{\gamma_2}{2}(\frac{\delta_2(\delta_1^2\gamma_2 + \delta_2^2\gamma_1)}{\gamma_2(\delta_1^2\gamma_2+\delta_2^2\gamma_1)})^2$$

$$= \frac{\delta_1^2}{\gamma_1} + \frac{\delta_2^2}{\gamma_2} - \frac{\delta_1^2}{2\gamma_1} - \frac{\delta_2^2}{2\gamma_2}$$

$$= \frac{\delta_1^2\gamma_2 + \delta_2^2\gamma_1}{2\gamma_1\gamma_2}$$

7.2 Appendix A2: Proof of Proposition 2

Given the initial sector is already established and that abatement from sector 1 is equal to the required abatement $\bar{A}_1 = A_1 = \frac{\delta_1}{\gamma_1}$. Proposition 1 demonstrates the optimal choices for $\bar{A}_2 = \frac{\delta_2}{\gamma_2}$ and $r = \frac{\delta_2}{\delta_1}$. I now demonstrate that after firms minimize costs, A_1^* will be equal to $\bar{A}_1$ and A_2^* will be equal to $\bar{A}_2$. Such that each sector will do exactly the amount of initial abatement required for their sector.

$$\bar{A}_1 = A_1 = \frac{\delta_1}{\gamma_1} \tag{21}$$

We solve for A_1^* and A_2^* by plugging in optimal choices for $\bar{A}_2$ and r.

$$A_1 = \frac{\bar{A}_1 + r\bar{A}_2}{1 + \frac{r^2\gamma_1}{\gamma_2}}$$

$$\text{Plugging in } \bar{A}_2 \text{ and } r \rightarrow$$

$$\begin{aligned} A_1 = \frac{\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\delta_1}\frac{\delta_2}{\gamma_2}}{1 + \frac{(\frac{\delta_2}{\delta_1})^2\gamma_1}{\gamma_2}} &= \frac{\frac{\delta_1}{\gamma_1}(1 + \frac{\delta_2^2}{\delta_1\gamma_2} * \frac{\gamma_1}{\delta_1})}{1 + \frac{(\frac{\delta_2}{\delta_1})^2\gamma_1}{\gamma_2}} \\ &= \frac{\delta_1}{\gamma_1} * \frac{1 + \frac{\delta_2^2\gamma_1}{\gamma_2\delta_1^2}}{1 + \frac{\delta_2^2\gamma_1}{\gamma_2\delta_1^2}} \\ &= \frac{\delta_1}{\gamma_1} = A_1^* \end{aligned} \tag{22}$$

$A_1 = A_1^* = \bar{A}_1$ representing that the initial quantity of abatement required by sector 1 is equal to the abatement done by sector 1 after extending the system.

Similarly for sector 2, the optimal choice for $\bar{A}_2 = \frac{\delta_2}{\gamma_2}$. We show that after setting the trading ratio and new abatement cap optimally, A_2^* will be equal to $\bar{A}_2$.

$$A_2 = \frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1} + r}$$

$$\text{Plugging in r equal to } \frac{\delta_2}{\delta_1} \text{ and } \bar{A}_2 = \frac{\delta_2}{\gamma_2}$$

$$\begin{aligned} A_2 = \frac{\frac{\delta_1}{\gamma_1} + r\frac{\delta_1}{\gamma_1}}{\frac{\gamma_2}{r\gamma_1} + r} &= \frac{r * \frac{\delta_1}{\gamma_1} + r^2\frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{\gamma_1} + r^2} \\ = \frac{\frac{\delta_2}{\delta_1} * \frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\delta_1}^2\frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{\gamma_1} + \frac{\delta_2}{\delta_1}^2} &= \frac{\frac{\delta_2}{\gamma_1} + \frac{\delta_2^3}{\delta_1^2\gamma_2}}{\frac{\gamma_2}{\gamma_1} + \frac{\delta_2}{\delta_1}^2} \\ = \frac{\frac{\delta_2\delta_1^2\gamma_2 + \delta_2^3\gamma_1}{\gamma_1\delta_1^2\gamma_2}}{\frac{\gamma_2\delta_1^2 + \delta_2^2\gamma_1}{\gamma_1\delta_1^2}} = \frac{\frac{\delta_2\delta_1^2\gamma_2 + \delta_2^3\gamma_1}{\gamma_2}}{\gamma_2\delta_1^2 + \delta_2^2\gamma_1} &= \frac{\frac{\delta_2\delta_1^2\gamma_2 + \delta_2^3\gamma_1}{\gamma_2}}{\gamma_2\delta_1^2 + \delta_2^2\gamma_1} \\ A_2 = \frac{\delta_2(\delta_1^2 + \frac{\delta_2^2\gamma_1}{\gamma_1})}{\gamma_2(\delta_1^2 + \frac{\delta_2^2\gamma_1}{\gamma_2})} &= \frac{\delta_2}{\gamma_2} = A_2^* \end{aligned} \tag{23}$$

7.3 Appendix A3: Proof of Proposition 3

First, suppose that the initial sector 1 is operating at a point where $p \neq MC_1(A_1) \neq \frac{\delta_1}{\gamma_1}$.

Firms will still minimize costs similar to Appendix A1 in which I solve for the outcomes A_1 and A_2. Now we can write the regulator's problem in terms of known parameters $\bar{A}_1$, γ_1, γ_2, and choice variables $\bar{A}_2$ and r.

$$\begin{aligned} \max_{\bar{A}_2, r} \quad TSW = \sum_i D_i(A_i) - \sum_i C_i(A_i) \\ = \delta_1\left(\frac{\bar{A}_1 + r\bar{A}_2}{1 + \frac{r^2\gamma_1}{\gamma_2}}\right) + \delta_2\left(\frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1} + r}\right) - \frac{\gamma_1}{2}\left(\frac{\bar{A}_1 + r\bar{A}_2}{1 + \frac{r^2\gamma_1}{\gamma_2}}\right)^2 - \frac{\gamma_2}{2}\left(\frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1} + r}\right)^2 \end{aligned} \tag{24}$$

Maximizing this equation with respect to $\bar{A}_2$ and r we arrive at choices for

$$\bar{A}_2 = \frac{1}{r}\left(\frac{\delta_1}{\gamma_1} - \bar{A}_1\right) + \frac{\delta_2}{\gamma_2} \tag{25}$$

If we plug in $r = \frac{\delta_2}{\delta_1}$ and $\bar{A}_2 = \frac{1}{r}(\frac{\delta_1}{\gamma_1} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}$. We can solve for total social welfare.

$$\delta_1\left(\frac{\bar{A}_1 + r\bar{A}_2}{1 + \frac{r^2\gamma_1}{\gamma_2}}\right) + \delta_2\left(\frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1} + r}\right) - \frac{\gamma_1}{2}\left(\frac{\bar{A}_1 + r\bar{A}_2}{1 + \frac{r^2\gamma_1}{\gamma_2}}\right)^2 - \frac{\gamma_2}{2}\left(\frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1} + r}\right)^2 \tag{26}$$

Plugging in the choices for r and $\bar{A}_2$ we reach the first-best total welfare solution as found in the proof of Proposition 1.

$$\begin{aligned} \delta_1\left(\frac{\bar{A}_1 + r(\frac{1}{r}(\frac{\delta_1}{\gamma_1} - \bar{A}_1) + \frac{\delta_2}{\gamma_2})}{1 + \frac{r^2\gamma_1}{\gamma_2}}\right) + \delta_2\left(\frac{\bar{A}_1 + r\frac{1}{r}(\frac{\delta_1}{\gamma_1} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{r\gamma_1} + r}\right) \\ - \frac{\gamma_1}{2}\left(\frac{\bar{A}_1 + r\frac{1}{r}(\frac{\delta_1}{\gamma_1} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{1 + \frac{r^2\gamma_1}{\gamma_2}}\right)^2 - \frac{\gamma_2}{2}\left(\frac{\bar{A}_1 + r\frac{1}{r}(\frac{\delta_1}{\gamma_1} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{r\gamma_1} + r}\right)^2 \end{aligned} \tag{27}$$

$$\begin{aligned} = \delta_1\left(\frac{\bar{A}_1 + \frac{\delta_2}{\delta_1}(\frac{1}{\frac{\delta_2}{\delta_1}}(\frac{\delta_1}{\gamma_1} - \bar{A}_1) + \frac{\delta_2}{\gamma_2})}{1 + \frac{\frac{\delta_2}{\delta_1}^2\gamma_1}{\gamma_2}}\right) + \delta_2\left(\frac{\bar{A}_1 + \frac{\delta_2}{\delta_1}\frac{1}{\frac{\delta_2}{\delta_1}}(\frac{\delta_1}{\gamma_1} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{\frac{\delta_2}{\delta_1}\gamma_1} + \frac{\delta_2}{\delta_1}}\right) \\ - \frac{\gamma_1}{2}\left(\frac{\bar{A}_1 + \frac{\delta_2}{\delta_1}\frac{1}{\frac{\delta_2}{\delta_1}}(\frac{\delta_1}{\gamma_1} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{1 + \frac{\frac{\delta_2}{\delta_1}^2\gamma_1}{\gamma_2}}\right)^2 - \frac{\gamma_2}{2}\left(\frac{\bar{A}_1 + \frac{\delta_2}{\delta_1}\frac{1}{\frac{\delta_2}{\delta_1}}(\frac{\delta_1}{\gamma_1} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{\frac{\delta_2}{\delta_1}\gamma_1} + \frac{\delta_2}{\delta_1}}\right)^2 \end{aligned} \tag{28}$$

$$= \delta_1 (\frac{\frac{\delta_1}{\gamma_1} + \frac{\delta_2^2}{\delta_1\gamma_2}}{1 + \frac{\delta_2\gamma_1}{\delta_1^2\gamma_2}}) + \delta_2 (\frac{\frac{\delta_1}{\gamma_1} + \frac{\delta_2^2}{\delta_1\gamma_2}}{\frac{\gamma_2}{\frac{\delta_2}{\delta_1^2}\gamma_1} + \frac{\delta_2}{\delta_1}}) - \frac{\gamma_1}{2} (\frac{\frac{\delta_1}{\gamma_1} + \frac{\delta_2^2}{\delta_1\gamma_2}}{1 + \frac{\delta_2\gamma_1}{\delta_1^2\gamma_2}})^2 - \frac{\gamma_2}{2} (\frac{\frac{\delta_1}{\gamma_1} + \frac{\delta_2^2}{\delta_1\gamma_2}}{\frac{\gamma_2}{\frac{\delta_2}{\delta_1^2}\gamma_1} + \frac{\delta_2}{\delta_1}})^2 \tag{29}$$

Solving this as was done in Proposition 1, we arrive at the first-best solution of TSW.

$$TSW^* = \frac{\delta_1^2\gamma_2 + \delta_2^2\gamma_1}{2\gamma_1\gamma_2} \tag{30}$$

7.4 Proof of Corollary 1

In this section, we demonstrate that in inefficient markets choices of $\bar{A}_2$ found in Proposition 3 are superior to choices for abatement that would have been selected given a system was designed from scratch. Since one sector is already operating the choice of $\bar{A}_1$ is fixed.

If policymakers were starting a system from scratch, they could designate permits to both sectors equivalent to where their marginal costs would equal their marginal damages (i.e. $\bar{A}_1 = \frac{\delta_1}{\gamma_1}$ and $\bar{A}_2 = \frac{\delta_2}{\gamma_2}$). Along with this, a trading ratio equal to $r = \frac{\delta_2}{\delta_1}$ would lead to the first-best outcome of the CAT system. This is similar to Proposition 1, where the first sector is operating efficiently. The total amount of permits in this system would be equal to:

$$\bar{A}_1 + \bar{A}_2 = \frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\gamma_2} \tag{31}$$

Now, this choice for the total amount of required abatement in (Eqn 31) is inefficient if the first sector is not operating optimally. Suppose we arrange (Eqn 31) such that our choice for $\bar{A}_2$ is a function of $\bar{A}_1$, δ_1, δ_2, γ_1, and γ_2.

$$\bar{A}_2 = \frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\gamma_2} - \bar{A}_1 \tag{32}$$

Using a trading ratio equal to $\frac{\delta_2}{\delta_1}$, plugging this choice for $\bar{A}_2$ into our TSW function we get.

$$
\begin{aligned}
TSW = \delta_1(\frac{\bar{A}_1 + r(\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\gamma_2} - \bar{A}_1) + \frac{\delta_2}{\gamma_2})}{1 + \frac{r^2\gamma_1}{\gamma_2}}) + \delta_2(\frac{\bar{A}_1 + r(\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\gamma_2} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{r\gamma_1} + r}) \\
-\frac{\gamma_1}{2}(\frac{\bar{A}_1 + r(\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\gamma_2} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{1 + \frac{r^2\gamma_1}{\gamma_2}})^2 - \frac{\gamma_2}{2}(\frac{\bar{A}_1 + r(\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\gamma_2} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{r\gamma_1} + r})^2
\end{aligned} \tag{33}
$$

Substituting in $r = \frac{\delta_2}{\delta_1}$

$$
\begin{aligned}
TSW = \delta_1(\frac{\bar{A}_1 + \frac{\delta_2}{\delta_1}(\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\gamma_2} - \bar{A}_1) + \frac{\delta_2}{\gamma_2})}{1 + \frac{\frac{\delta_2}{\delta_1}^2\gamma_1}{\gamma_2}}) + \delta_2(\frac{\bar{A}_1 + \frac{\delta_2}{\delta_1}(\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\gamma_2} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{\frac{\delta_2}{\delta_1}\gamma_1} + \frac{\delta_2}{\delta_1}}) \\
-\frac{\gamma_1}{2}(\frac{\bar{A}_1 + \frac{\delta_2}{\delta_1}(\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\gamma_2} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{1 + \frac{\frac{\delta_2}{\delta_1}^2\gamma_1}{\gamma_2}})^2 - \frac{\gamma_2}{2}(\frac{\bar{A}_1 + \frac{\delta_2}{\delta_1}(\frac{\delta_1}{\gamma_1} + \frac{\delta_2}{\gamma_2} - \bar{A}_1) + \frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{\frac{\delta_2}{\delta_1}(\gamma_1} + \frac{\delta_2}{\delta_1}})^2
\end{aligned} \tag{34}
$$

$$
\begin{aligned}
TSW_q = \delta_1(\frac{(1 - \frac{\delta_2}{\delta_1})\bar{A}_1 + \frac{\delta_2}{\gamma_1} + \frac{\delta_2^2}{\delta_1\gamma_2} + \frac{\delta_2}{\gamma_2}}{1 + \frac{\delta_2^1\gamma_1}{\delta_1^2\gamma_2}}) + \delta_2(\frac{(1 - \frac{\delta_2}{\delta_1})\bar{A}_1 + \frac{\delta_2}{\gamma_1} + \frac{\delta_2^2}{\delta_1\gamma_2} + \frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{\frac{\delta_2}{\delta_1}\gamma_1} + \frac{\delta_2}{\delta_1}}) \\
-\frac{\gamma_1}{2}(\frac{(1 - \frac{\delta_2}{\delta_1})\bar{A}_1 + \frac{\delta_2}{\gamma_1} + \frac{\delta_2^2}{\delta_1\gamma_2} + \frac{\delta_2}{\gamma_2}}{1 + \frac{\delta_2^2\gamma_1}{\delta_1^2\gamma_2}})^2 - \frac{\gamma_2}{2}(\frac{(1 - \frac{\delta_2}{\delta_1})\bar{A}_1 + \frac{\delta_2}{\gamma_1} + \frac{\delta_2^2}{\delta_1\gamma_2} + \frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{\frac{\delta_2}{\delta_1}\gamma_1} + \frac{\delta_2}{\delta_1}})^2
\end{aligned} \tag{35}
$$

Simplifying this equation, $TSW_q < TSW^*$ if all parameters are positive. This demonstrates that choices of $\bar{A}_2^*$ from Proposition 3 result in greater welfare than choosing $\bar{A}_2$ equal to the leftover required abatement from the inefficiently set first sector.

7.5 Appendix A4: Proof of Proposition 4

In this appendix, I demonstrate that while using a trading ratio of one, no choice for $\bar{A}_2$ will obtain a first-best outcome if the initial sector is inefficient ($\bar{A}_1 \neq \frac{\delta_1}{\gamma_1}$). Suppose $r = 1$ and regulators optimally choose $\bar{A}_2$ to maximize total social welfare. Knowing how firms will reach their abatement targets through trade or abatement the regulator's problem simplifies too:

$$
\max\ TSW_{\bar{A}_2} = \delta_1(\frac{\bar{A}_1 + \bar{A}_2}{1 + \frac{\gamma_1}{\gamma_2}}) + \delta_2(\frac{\bar{A}_1 + \bar{A}_2}{\frac{\gamma_2}{\gamma_1} + 1}) - \frac{\gamma_1}{2}(\frac{\bar{A}_1 + \bar{A}_2}{1 + \frac{\gamma_1}{\gamma_2}})^2 - \frac{\gamma_2}{2}(\frac{\bar{A}_1 + \bar{A}_2}{\frac{\gamma_2}{\gamma_1} + 1})^2 \tag{36}
$$

The first order conditions with respect to the choice of $\bar{A}_2$ are:

$$\begin{aligned} \text{FOC:} \quad \frac{\partial TW}{\partial \bar{A}_2} &= (\frac{\delta_1}{1+\frac{\gamma_1}{\gamma_2}}) + (\frac{\delta_2}{\frac{\gamma_2}{\gamma_1}+1}) - \gamma_1(\frac{\bar{A}_1+\bar{A}_2}{1+\frac{\gamma_1}{\gamma_2}})(\frac{1}{1+\frac{\gamma_1}{\gamma_2}}) - \gamma_2(\frac{\bar{A}_1+\bar{A}_2}{\frac{\gamma_2}{\gamma_1}+1})(\frac{1}{\frac{\gamma_2}{\gamma_1}+1}) = 0 \\ \rightarrow \bar{A}_2 &= \frac{\delta_1\gamma_2+\delta_2\gamma_1-\gamma_2\gamma_1\bar{A}_1}{\gamma_1\gamma_2} = \frac{\delta_2}{\gamma_2}+\frac{\delta_1}{\gamma_1}-\bar{A}_1 \end{aligned} \tag{37}$$

Now plugging in this $\bar{A}_2$ into the total welfare when the trading ratio is equal to one, the TSW function simplifies to zero. This is less than the optimal total social welfare function of optimal total social welfare function when the trading ratio is not equal to one.

$$TSW^* = \frac{\delta_1^2\gamma_2+\delta_2^2\gamma_1}{2\gamma_1\gamma_2} > 0$$

7.6 Appendix A5: Proof of Proposition 5

This appendix proves that if abatement requirements are constrained such that $\bar{A}_2 = \frac{\delta_2}{\gamma_2}$, no choice of trading ratio can be used to achieve a first-best solution if the initial cap is set inefficiently. If the initial cap is set inefficiently such that $\bar{A}_1 \neq \frac{\delta_1}{\gamma_1}$. The regulators will try and maximize TSW by their choice of trading ratio (r).

$$\max_r \ TSW = \delta_1(\frac{\bar{A}_1+r\bar{A}_2}{1+\frac{r^2\gamma_1}{\gamma_2}}) + \delta_2(\frac{\bar{A}_1+r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1}+r}) - \frac{\gamma_1}{2}(\frac{\bar{A}_1+r\bar{A}_2}{1+\frac{r^2\gamma_1}{\gamma_2}}) - \frac{\gamma_2}{2}(\frac{\bar{A}_1+r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1}+r}) \tag{38}$$

$$\frac{\partial TW}{\partial r} = \frac{\gamma_2(\bar{A}_2(\gamma_2-r^2\gamma_1)-2\bar{A}_1r\gamma_1)(\gamma_1\gamma_2(\bar{A}_1+r\bar{A}_2+\delta_1(r^2\gamma_1+\gamma_2))) + \gamma_1(\bar{A}_1r^2\gamma_1-\bar{A}_1\gamma_2-2\bar{A}_2r\gamma_2)(\bar{A}_1r\gamma_1\gamma_2+r^2(\bar{A}_2\gamma_1\gamma_2-\delta_2\gamma_1)-\delta_2\gamma_2)}{(r^2\gamma_1+\gamma_2)^3} = 0 \tag{39}$$

$$r^* = \frac{\sqrt{\gamma_1}\sqrt{\gamma_2}\sqrt{\bar{A}_2\gamma_2\gamma_1^2-4\bar{A}_1\delta_1\gamma_2\gamma_1+\bar{A}_2{}^2\gamma_2^2\gamma_1-4\bar{A}_2\delta_2\gamma_2\gamma_1+4\delta_1^2\gamma_2+4\delta_2^2\gamma_1-\bar{A}_2{}^2\gamma_2\gamma_1^2+2\bar{A}_1\delta_1\gamma_2\gamma_1\bar{A}_2{}^2\gamma_2^2\gamma_1-2\bar{A}_2\delta_2\gamma_2\gamma_1}}{2(\gamma_2\gamma_1^2\bar{A}_1\bar{A}_2-\delta_2\gamma_1^2\bar{A}_1-\delta_1\gamma_1\gamma_2\bar{A}_2)} \tag{40}$$

Plugging in this solution of r into our total welfare function with $\bar{A}_2 = \frac{\delta_2}{\gamma_2}$, this is not equal to the optimal TSW^*. If $\bar{A}_1 = \frac{\delta_1}{\gamma_1}$ and $\bar{A}_2 = \frac{\delta_2}{\gamma_2}$ then this formula for r^* simplifies to $\frac{\delta_2}{\delta_1}$.

7.6.1 Proof of Corollary 2

In this proof, we demonstrate that if regulators were able to manipulate the required abatement from the existing sector, this would be equivalent to manipulating the abatement required from the new sector. For example, if regulators could set $\bar{A}_1$ and $\bar{A}_2$ such that $\bar{A}_1 + \bar{A}_2 = \frac{\delta_1}{\gamma_1} + r\frac{\delta_2}{\gamma_2}$.

This is equivalent to the social planner problem in equation (17); however, now we have three choice variables $(\bar{A}_2, r, \bar{A}_1)$.

$$\max_{\bar{A}_2, r, \bar{A}_2} \quad TSW = \sum_i D_i(A_i) - \sum_i C_i(A_i)$$
$$= \delta_1(\frac{\bar{A}_1 + r\bar{A}_2}{1 + \frac{r^2\gamma_1}{\gamma_2}}) + \delta_2(\frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1} + r}) - \frac{\gamma_1}{2}(\frac{\bar{A}_1 + r\bar{A}_2}{1 + \frac{r^2\gamma_1}{\gamma_2}})^2 - \frac{\gamma_2}{2}(\frac{\bar{A}_1 + r\bar{A}_2}{\frac{\gamma_2}{r\gamma_1} + r})^2 \tag{41}$$

Using the optimal trading ratio $r = \frac{\delta_2}{\delta_1}$ and setting the numerator of each fraction in the TSW function such that $\bar{A}_1 + r\bar{A}_2 = \frac{\delta_1}{\gamma_1} + (\frac{\delta_2}{\delta_1})\frac{\delta_2}{\gamma_2}$. Plugging this into the numerator of our TSW problem we get:

$$= \delta_1(\frac{\frac{\delta_1}{\gamma_1} + (\frac{\delta_2}{\delta_1})\frac{\delta_2}{\gamma_2}}{1 + \frac{r^2\gamma_1}{\gamma_2}}) + \delta_2(\frac{\frac{\delta_1}{\gamma_1} + (\frac{\delta_2}{\delta_1})\frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{r\gamma_1} + r}) - \frac{\gamma_1}{2}(\frac{\frac{\delta_1}{\gamma_1} + (\frac{\delta_2}{\delta_1})\frac{\delta_2}{\gamma_2}}{1 + \frac{r^2\gamma_1}{\gamma_2}})^2 - \frac{\gamma_2}{2}(\frac{\frac{\delta_1}{\gamma_1} + (\frac{\delta_2}{\delta_1})\frac{\delta_2}{\gamma_2}}{\frac{\gamma_2}{r\gamma_1} + r})^2 \tag{42}$$

This solution is similar to that in Appendix A1 and Appendix A3 where only the numerators of the TSW function are changed. This simplifies total social welfare to the optimal solution.

$$TSW^* = \frac{\delta_1^2\gamma_2 + \delta_2^2\gamma_1}{2\gamma_1\gamma_2}$$

7.7 Appendix A7: Sensitivity Analysis

In this section, I perform a variety of sensitivity analysis on the simulation model of the EU ETS expansion into aviation. These sensitivity analysis include manipulation of the marginal abatement cost parameter for the aviation sector, the social cost of carbon estimates, the ratio of marginal benefits of abatement between sectors, the functional form of the marginal abatement cost curves, and the growth of the aviation sector.

First, I compute a sensitivity analysis around the marginal abatement cost parameter of the aviation sector. These parameters are not as commonly estimated in the literature as aviation firms have just recently been exposed to more strict emission regulations. Our main specification uses a marginal abatement cost parameter of 61 euros per million tonnes of CO_2 abatement. I vary this parameter to three levels: low (40), medium (60), and high (80). Table A7.1 displays the welfare results from alternative choices of policy instruments with alternative aviation marginal abatement cost parameters (γ_2).

Table A7.1: Sensitivity Analysis Aviation Marginal Abatement Cost Parameter

	Aviation Marginal Costs		
	Low	Medium	High
Policy Choices	γ_2 =40	γ_2 =61	γ_2 =80
$\bar{A}_2 = 2$, $r = 1$	0.09%	**0%**	-0.04%
$\bar{A}_2 = 2$, $r = 3$	1.46%	1.37%	1.33%
$\bar{A}_2 = 2$, $r = 13.6$	-3.1%	0.37%	2.07%
$\bar{A}_2 = 10$, $r = 1$	2.84%	2.74%	2.70%
$\bar{A}_2 = 10$, $r = 3$	9.32%	9.21%	9.16%
$\bar{A}_2 = 10$, $r = 13.6$	20.77%	24.70%	26.63%

Note: Changes of welfare are compared to baseline scenario of $\bar{A}_2 = 2$, $r = 1$, and $\gamma_2 = 61$.

Next, I examine the sensitivity of my simulation to the social cost of carbon estimates. A crucial piece of designing an efficient cap-and-trade system is that marginal damages are equal to the marginal costs of abatement. The SCC is an estimate of avoided marginal damages equal to our future marginal benefits of abatement. Marginal damage estimates for greenhouse gas emissions have, however, changed over the last decade. As this policy was designed around 2010 and implemented

Table A7.2: Welfare Sensitivity Analysis Under Alternative estimates of Marginal Damages (δ_1 & δ_2)

Policy Choices	Low δ_1 =16.60 δ_2 =49.80	Medium δ_1 =100 δ_2 =300	High δ_1 =175 δ_2 =525
$\bar{A}_2 = 2$, $r = 1$	0%	0%	0%
$\bar{A}_2 = 2$, $r = 3$	1.37%	1.79%	1.82%
$\bar{A}_2 = 2$, $r = 13.6$	0.37%	2.99%	3.20%
$\bar{A}_2 = 10$, $r = 1$	2.74%	3.80%	3.88%
$\bar{A}_2 = 10$, $r = 3$	9.21%	13.12%	13.43%
$\bar{A}_2 = 10$, $r = 13.6$	24.70%	49.15%	51.07%

Note: Changes of welfare are compared to baseline scenario of each realization of marginal damages $\{\delta_1, \delta_2\}$ with $\bar{A}_2 = 2$, $r = 1$, and $\gamma_2 = 61$.

in 2012 SCC estimates were much lower than they are in 2024.[20] Therefore, evaluating this policy ten years after its implementation, our ex-post analysis uses SCC estimates of $\delta_1 = 16.60$. Although this is what regulators would have expected at the time of designing the policy, we compare the welfare gains to alternative scenarios if the SCC at the time was more aligned with consensus SCC estimates in 2024 (around \$200). Table A7.2 presents welfare results if marginal damages from carbon emissions were estimated differently. At the time of the policy implementation (2012), economists and policymakers may have had a much different estimate of marginal damages from greenhouse gas emissions. Today estimates for the social cost of carbon are around 10x larger than what were used in 2012. Table A7.2 compares the welfare changes of alternative choices of trading ratios and abatement requirements under different social cost of carbon estimates. The ratio of marginal damages from stationary sources in the EU ETS (δ_1) to marginal damages from aviation (δ_2) is kept constant at three. However, the estimates for the SCC are increased to €100 and €175. Table A7.2 displays the percentage of welfare changes compared to the original policy parameter chosen. Across low, medium, and high marginal damages, we see a similar pattern in which higher trading ratios and abatement requirements would increase welfare. The largest welfare gains come from $\bar{A}_2 = 10$ and $r = 13.6$.

Next, Table A7.3 examines our welfare results when using abatement cost functions have alter-

[20]This paper was written in 2024, therefore the most accurate estimates of the social cost of carbon in 2024 were around €200.

native functional forms. In many models, abatement costs are assumed to be quadratic (Woerman, 2023; Fowlie and Muller, 2019). However, IAMs such as DICE also use alternative abatement cost functional forms. Table A7.3 displays changes in welfare using alternative functional forms of abatement costs in the existing EU ETS. This table displays welfare changes under low ($\frac{\gamma_1}{2}(A_1)^{1.4}$), medium ($\frac{\gamma_1}{2}(A_1)^{2}$), and high ($\frac{\gamma_1}{2}(A_1)^{2.6}$) marginal abatement costs. Welfare is highest when abatement requirements for the new sector are extended to 10 million and trading ratios of 13.6 are used. However, Welfare estimates do fluctuate slightly depending on which functional form is used.

Table A7.3: Welfare Changes from Alternative Functional Forms of Abatement Costs

	Marginal Cost		
	Low	Medium	High
Policy Choices	$\frac{\gamma_1}{2}(A_1)^{1.4}$	$\frac{\gamma_1}{2}(A_1)^{2}$	$\frac{\gamma_1}{2}(A_1)^{2.6}$
$\bar{A}_2 = 2$, $r = 1$	0%	0%	0%
$\bar{A}_2 = 2$, $r = 3$	1.7%	1.37%	1.2%
$\bar{A}_2 = 2$, $r = 13.6$	1.0%	0.37%	-0.6%
$\bar{A}_2 = 10$, $r = 1$	4.0%	2.74%	2.4%
$\bar{A}_2 = 10$, $r = 3$	13.5%	9.21%	7.7%
$\bar{A}_2 = 10$, $r = 13.6$	18.9%	24.70%	12.3%

Note: Changes of welfare are compared to a baseline scenario with $\delta_1 = 16.6$, $\delta_1 = 49.8$ and $\gamma_2 = 61$.

Finally, we examine how sensitive our results are to changes in emissions growth in the aviation sector. Aviation tends to be one of the fastest-rising emissions sectors in the world. The estimated average projected annual growth rate of aviation is about 4.2-5.1% (IATA, 2009). Due to this growth, it may be difficult for regulators to estimate the BAU emissions from this sector and, in turn, give out the required amount of permits. Table A7.4 shows welfare calculations under alternative BAU emissions scenarios. If the aviation industry is growing, the abatement of 2 million tonnes of emissions may be an underestimate of the required abatement from the sector. Therefore, this table analyzes how welfare would have changed under higher abatement requirements. We see that even with higher abatement requirements welfare would increase due to the cost of this abatement being lower than the avoided damages from these emissions.

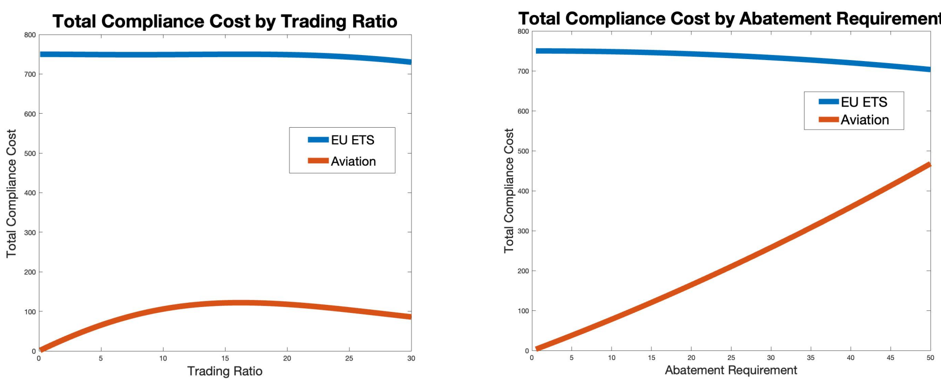
Table A7.4: Welfare Changes under Alternative Aviation Emissions Growth

	Growth in Aviation Emissions		
	Low	Medium	High
Policy Choices	$\bar{A}_2 = 2$	$\bar{A}_2 = 4$	$\bar{A}_2 = 6$
$r = 1$	0%	0%	0%
$r = 3$	1.37%	2.6%	4.0%
$r = 13.6$	0.37%	7.1%	12.9%

Note: Changes of welfare are compared to the baseline scenario of each realization of marginal damages $\{\delta_1, \delta_2\}$ with $r = 1$, $\gamma_1 = 0.0375$ and $\gamma_2 = 61$.

7.8 Appendix A8: Distribution Graphs

Figure A1 presents total compliance costs for the aviation industry and the EU ETS based on alternative choices of trading ratios (Panel A) and aviation abatement requirements (Panel B).



(a) By Trading Ratio

(b) By Abatement Requirement

Figure A1: Distribution of Compliance Costs