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Strategic Residual Emissions in Net Emission Targets

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Abstract

The concept of net emission targets requires balancing out remaining residual emissions with carbon removals. While an increasing number of countries is adopting net emission targets, it remains unclear how governments choose the level of residual emissions at which they plan to achieve them. This paper sheds light on the matter by examining the role of strategic environmental policy when a regional government unilaterally chooses the mix of abatement and removal to achieve an exogenous net emission target. Using a theoretical model of two regions that trade a polluting good and removals on the international market, I find that governments have an incentive to deviate from first-best residual emissions to improve domestic welfare. Under perfect competition, the sign and size of the distortion is driven by the *terms-of-trade effect* and a new *removal trade balance effect*, giving rise to inefficiently high levels of residual emissions in some cases (*removal dumping*). I derive optimal carbon prices and discuss removal obligations as policy instruments to implement the unilaterally optimal mix in a decentralized economy. Finally, I show that the incentive for strategic behavior by the domestic government is influenced by the *type* of net emission target in the foreign region.

Keywords: Strategic Environmental Policy, Net Emission Targets, Residual Emissions, Carbon Dioxide Removal, Removal Dumping

Because Europe will do “whatever it takes” to keep its competitive edge.

— Ursula von der Leyen

State of the Union Address, September 2023

1 Introduction

The science is clear: to achieve the goals of the Paris Agreement the world needs to reach net-zero emissions by mid-century, requiring both drastic emission reductions and the scale-up of carbon dioxide removal technologies (IPCC, 2022). Following the scientific evidence, the concept of net-zero emissions has emerged as a new focal point of climate policy. As shown in Figure 1, an increasing number of countries is enshrining net-zero targets in national climate legislation or policy documents. However, Buck et al. (2023) find that the majority of published net-zero strategies remains unclear about the level of residual emissions and the envisioned role of carbon removal at the time of net zero. Moreover, countries with quantified net-emission targets project that residual emissions will amount to, on average, 18 percent of current emissions. As projections of high levels of residual emissions can result in unsustainable or unfeasible levels of carbon removal, it is important to understand which factors influence the projected level of residual emissions in net-emission targets (Buck et al., 2023).

In general, the choice of residual emissions might be influenced by a variety of factors. Most importantly, the level of residual emissions might not only depend on what is technically feasible to abate, but also on political and economic considerations such as anticipated carbon leakage or concerns about the competitiveness of local industries in hard-to-abate sectors (Schenuit et al., 2023; Edenhofer et al., 2023). As for the carbon leakage concern, Franks et al. (2023) show that the optimal unilateral climate policy consists in subsidizing carbon removal at a higher rate than the tax on emissions because carbon removal does not induce any supply-side leakage on the energy market. Consequently, it seems plausible that a unilateral net-emission target would rely on more carbon removal and less abatement to protect against this carbon leakage channel. In contrast, the competitiveness concern in the context of net-emission targets has not yet been studied in the economic literature. This paper addresses this research gap.

Building on the literature in strategic environmental policy, I analyze a theoretical model of two economic regions that trade a polluting good and carbon removal on the world market. To focus on strategic incentives arising from exposure to international competition, I abstract from carbon leakage and assume that both regions need to comply with an *exogenous* net-emission

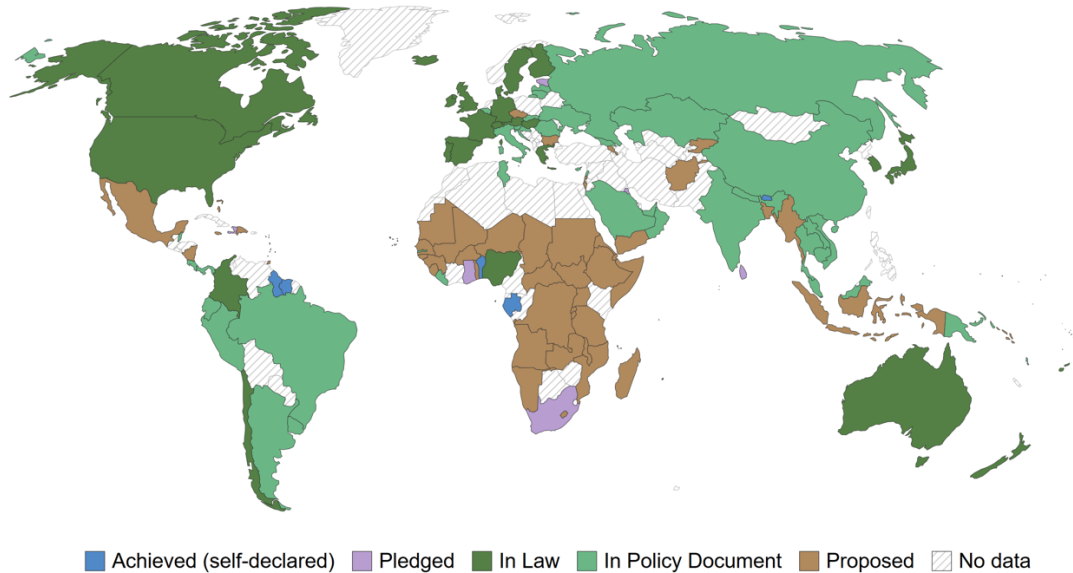


Figure 1: Status of net-zero carbon emissions targets. Published targets cover more than three-quarters of the world's global greenhouse gas emissions (World Resources Institute, 2023) Source: Our World in Data.

target. Thus, governments choose the mix of abatement and removal that maximizes domestic welfare subject to a given target. I find that if no other trade policy measures are available (for example due to WTO restrictions), exposure to international competition introduces an incentive to unilaterally deviate from the first-best levels of residual emissions. In particular, the *terms-of-trade effect* and the new *removal trade balance effect* cause governments to depart from the principle of equal marginal abatement and marginal removal cost. Under perfect competition, the *terms-of-trade effect* provides an incentive to influence the world market price by changing the production cost of the domestic industry. While a net-importing region would lower production cost by allowing higher residual emissions, a net-exporting region would decrease residual emissions relative to first-best to improve the terms-of-trade of the domestic industry. Similarly, the *removal trade balance effect* describes the incentive to influence the world market price for removals by taxing or subsidizing domestic removal demand. Put together, the net effect on residual emissions in net-emission targets is ambiguous and depends on the signs and the relative size of both effects. Consequently, the concern that exposure to international competition will lead to "weak net-emission targets", where "weak" refers to marginal abatement cost below marginal removal cost, is not always warranted. In fact, the findings suggest that some regions might even have an incentive to set a "strong" net-emission target. However, I show that in the special case of imperfect competition and domestic procurement of removals, governments have a clear incentive to engage in "removal dumping" and to set a weak net-emission target.

In addition, I discuss how the *type* of net-emission target in the foreign region affects the incentive for strategic behavior by the domestic government. While a given net-emission target can in principal be achieved with a variety of policy instruments, I show that a foreign *fixed* net-emission target with a fixed cap on emissions and removals makes the policy intervention by the domestic government more effective. However, the foreign region has an incentive to set a *flexible* target that allows emissions and removals to adapt to changing market conditions. Finally, I show that a flexible net-emission target cannot be implemented via carbon pricing and discuss removal obligations for firms as a possible alternative.

The remainder of the paper is structured as follows. First, I summarize key results from the related literature on strategic environmental policy in section 2. Then, I present the model set-up and derive the main results for the optimal unilateral policy under an exogenous net-emission target in section 3, followed by an extension to international removal markets in section 4. In section 5, I discuss the impact of the type of net-emission target on the incentive for strategic behavior. Finally, I discuss possible extensions and conclude in section 6.

2 Strategic Environmental Policy

The fact that the presence of international trade can have important implications for the stringency of environmental regulation is well known. In particular, the literature on strategic environmental policy investigates how environmental policy can be used as trade policy in order to increase the rents of the domestic firms. This question becomes particularly important when trade policies like tariffs or export subsidies are ruled out by free-trade agreements (Conrad, 1993).

In the case of perfect competition on the international market, Markusen (1975) showed that an exporting country can increase the profits of the domestic industry by taxing emissions at a rate higher than the domestic marginal damage. That is, by over-internalizing the environmental damage the exporting country can artificially increase the price for the exported product and thereby improve the terms-of-trade for the domestic industry. Conversely, if the country is a net importer, it has an incentive to under-internalize the environmental damage in order to increase domestic production and to decrease import cost. This describes the *terms-of-trade effect* of environmental policy (Requate, 2006). Hence, the optimal *second-best* unilateral tax rate deviates from the *first-best* (Pigouvian) unilateral tax rate because the environmental

regulation targets both the reduction of the domestic environmental damage as well as the maximization of the profits of the domestic industry.

In the case of imperfect competition on the international market, several authors have shown that the optimal second-best environmental regulation under-internalizes the domestic marginal damage (see e.g., Conrad, 1993; Barrett, 1994). The reason is that if markets are imperfectly competitive, the environmental regulation addresses both imperfect competition at home as well as the market power of the domestic firms on the international market (Requate, 2006). Both effects work towards a less stringent environmental regulation. First, due to imperfect competition on the international market, domestic consumer surplus is lowered by the shortage of supply. Since a stringent environmental regulation would further increase this quantity shortage, the *imperfect competition effect* causes the regulator to decrease the stringency of the regulation (Requate, 2006). Second, the regulator can expand the market share of the domestic firms by decreasing the stringency of the environmental regulation and thereby shift rents from the foreign country to the domestic country. This describes the *rent-shifting effect* of environmental policy (Requate, 2006). This effect is well known from the literature on strategic trade policy and has first been described by Brander and Spencer (1985).

In their seminal paper, Brander and Spencer (1985) use a model of two countries that engage in Cournot competition on the international market and show that the optimal unilateral trade policy consists in making exports cheaper by paying an export subsidy to the domestic firm. At first glance, this result is counterintuitive because the export subsidy lowers the world market price and therefore worsens the country's terms-of-trade. However, Brander and Spencer (1985) show that the negative *terms-of-trade effect* is more than offset by an increase in the profits of the domestic firm. The reason is that the subsidy leads to a shift of the domestic reaction function and thereby alters the market equilibrium in favor of the domestic firm. In particular, the domestic government can use the subsidy to move the domestic firm to the position of the Stackelberg leader. In consequence, the domestic firm captures a larger share of the market and rents are shifted from the foreign firm to the domestic firm. As the authors demonstrate, this *rent-shifting effect* outweighs the *terms-of-trade effect*.

In the case of environmental policy, the *rent-shifting effect* arises because under-internalizing the domestic marginal damage constitutes an indirect subsidy for the exports of the domestic firm. The practice of indirectly subsidizing domestic exports by weakening the domestic environmental regulation is also sometimes referred to as *environmental dumping* (Requate, 2006).

In sum, the literature on strategic environmental policy shows that governments have an incentive to alter the stringency of environmental regulation in order to increase domestic welfare. In particular, these incentives become relevant when environmental targets are chosen endogenously. In the following, I build on the literature in strategic environmental policy and show that the possibility of carbon removal opens up a new avenue for strategic environmental policy in the case of *exogenous* targets.

3 Strategic Environmental Policy with Net Emission Targets

3.1 Model Set-Up

Consider an economy with two regions $i \in \{D, F\}$. The *domestic* region D represents a large economic union with a single government, while the *foreign* region F represents a large number of small countries that act as price takers.¹ Each region consists of a representative household, perfectly competitive firms and a government. Households consume a homogeneous polluting good x that is produced by firms in both regions and traded on the world market at price P . Furthermore, assume that both regions are subject to exogenous net-emission targets, that is, emissions e^i net of removals r^i cannot exceed the budget \bar{E}^i .

$$\bar{E}^i \geq e^i - r^i \quad (1)$$

Households

Households in both regions spend their income y^i on the consumption of a numeraire z or the polluting good x . They maximize utility according to a quasi-linear utility function

$$\begin{aligned} U^i(x^i, z^i) &= u^i(x^i) + z^i \\ &= \int_0^{x^i} p^i(t) dt + z^i \end{aligned} \quad (2)$$

subject to the budget constraint $y^i = z^i + Px^i$. The utility derived from consuming x^i units of the polluting good is denoted by $u^i(x^i)$, while $p^i(t) = \frac{\partial U^i}{\partial x^i}$ represents the inverse demand function of the household.

¹Where no ambiguity arises, I suppress the regional index for the domestic region for ease of notation.

Firms

Firms in both regions produce q^i units of the homogeneous polluting good and sell them on the perfectly competitive world market at price $P = P(q^D + q^F) = P(Q)$. The cost of production are given by the convex cost function $C^i(q^i, e^i)$ and depend on both the level of output and emissions. Following Phaneuf and Requate (2016) and denoting partial derivatives as subscripts, the cost function has the following properties.

Assumption 1. $C^i(q, e)$ is twice continuously differentiable with $C_q^i > 0$, $C_{qq}^i > 0$, and for any production level q there is an emission level \hat{e}^q with zero abatement cost ($-C_e^i(q, \hat{e}^q) = 0$).

Furthermore

$$-C_e^i(q, e) > 0 \quad \forall e < \hat{e}^q \quad (3)$$

$$-C_e^i(q, e) < 0 \quad \forall e > \hat{e}^q \quad (4)$$

and

$$C_{qe}^i(q, e) = C_{eq}^i(q, e) < 0 \quad \forall e < \hat{e}^q \quad (5)$$

$$-C_{ee}^i(q, e) < 0 \quad \forall e < \hat{e}^q \quad (6)$$

$$C_{qq}^i C_{ee}^i - (C_{qe}^i)^2 > 0 \quad (7)$$

Assumption 1 states that the marginal cost of production C_q^i are increasing and that for any level of production q there is a cost-minimizing level of emissions \hat{e}^q . If environmental regulation causes emissions to be below this optimal level, the firm incurs increasing marginal abatement cost $-C_e^i > 0$ and faces higher marginal cost of production ($C_{qe}^i < 0$). Conversely, marginal abatement cost for any given level of emissions increase if the quantity produced increases ($-C_{eq}^i > 0$).

Firms can also remove emissions from the atmosphere. The cost of removing r^i units of emissions are given by the convex function $h_i(r)$. Using a prime to denote partial derivatives, the cost function has the following properties.

Assumption 2. $h_i(r)$ is twice continuously differentiable with $h_i' > 0$ and $h_i'' > 0$.

In the absence of regulation, the firm's profit function is given by

$$\pi^i(q^i, e^i, r^i) = Pq^i - C^i(q^i, e^i) - h_i(r^i) \quad (8)$$

Perfect competition on the world market implies the following first-order conditions.

$$C_q^i = P \quad (9)$$

$$-C_e^i = 0 \quad (10)$$

$$h_i' = 0 \quad (11)$$

Equation (9) states that firms produce output q^i until marginal cost of production equal the market-clearing world market price P . Equations (10) - (11) state that in the absence of environmental regulation firms will set marginal abatement cost and marginal removal cost equal to zero. Hence, without environmental policy there are no incentives for emission reductions or carbon removal.

Government

The government in the domestic region considers welfare as the sum of domestic consumer surplus and firm profits.

$$\begin{aligned} W(x, q, e, r) &= U(x, z) + \pi(q, e, r) \\ &= \int_0^x p(t)dt - C(q, e) + P[q - x] - h(r) \end{aligned} \quad (12)$$

where we have substituted z into (2) and dropped constant income y for ease of notation. As domestic production q might differ from consumption x , the term $P[q - x]$ reflects the value of net exports.

3.2 Social Planner Solution

As a benchmark, consider the optimization problem of the social planner. The social planner maximizes global welfare and takes into account the net emission targets in both regions. The constrained maximization problem is

$$\max_{\{x^i, q^i, e^i, r^i\}} \mathcal{L} = \sum_i (W^i(q^i, x^i, e^i, r^i) + \mu_i[\bar{E}^i - e^i + r^i]) \quad (13)$$

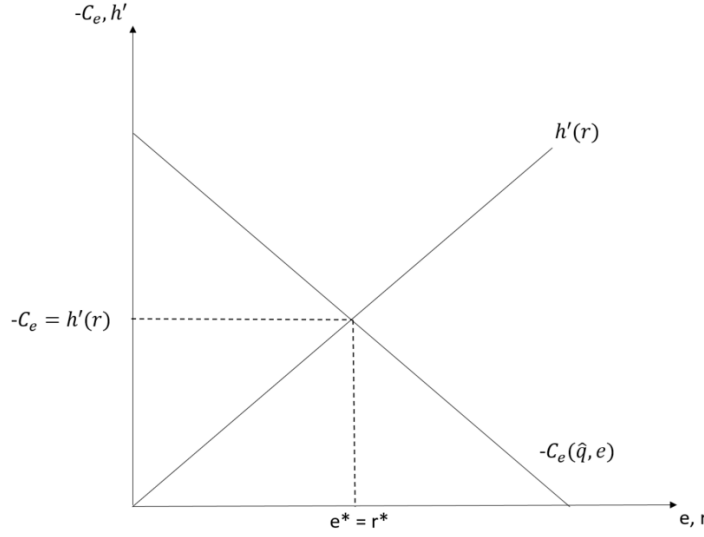


Figure 2: Efficient residual emissions for a given level of production \hat{q} .

where μ_i is the shadow price of the region-specific net-emission target $\bar{E}^i = e^i - r^i$. The first-order conditions describe the first-best allocation.

$$p^i(x^i) = P \quad (14)$$

$$C_{q_i}^i = P \quad (15)$$

$$-C_{e_i}^i = \mu_i \quad (16)$$

$$h'_i = \mu_i \quad (17)$$

It follows from (16) and (17) that $-C_{e_i}^i = h'_i$. Hence, the social planner achieves the net-emission targets by choosing emissions and removal quantities such that marginal abatement cost and marginal removal cost are equalized in each region.²

The special case of a regional *net-zero emission target* ($\bar{E}^i = 0$) is illustrated in Figure 2. In this case, the remaining *residual emissions* need to be offset by carbon removals. While in principle a net-zero emission target could be achieved with any mix of abatement and removals that satisfies $e^i - r^i = 0$, the efficient level of residual emissions is pinned down by the equality of marginal abatement cost and marginal removal cost. As noted by Edenhofer et al. (2023), the efficient level of residual emissions also ensures the fiscal balance of carbon tax revenue and the expenditure for a removal subsidy.

²In the case of a *global* net-emission target, the social planner would equate marginal abatement cost and marginal removal cost *within and across* regions (see Appendix A).

3.3 Unilateral Residual Emissions Policy

Suppose now that the government in region D unilaterally chooses the mix of abatement and removals to achieve its regional net-emission target. As we will see, the possibility to remove emissions from the atmosphere gives rise to a strategic incentive to deviate from the first-best allocation chosen by the social planner. However, the direction of the distortion depends on the assumed market structure. Hence, we consider both perfect competition and imperfect competition on the international market. In the following, we first derive the rules for the optimal mix of abatement and removal under a *command-and-control* policy regime and then establish optimal carbon prices for emissions and removals.

3.4 Command-and-Control

With a *command-and-control* policy regime, the government directly chooses the quantity of emissions and removals that maximize domestic welfare. Such a policy regime could, for example, be a cap on emissions with the cap being equal to the optimal level of emissions, in combination with (tradable) removal quotas for firms. We first analyze the case of perfect competition on the international market.

Perfect Competition

The government maximizes domestic welfare subject to the net-emission constraint \bar{E} . The constrained maximization problem becomes

$$\max_{\{e, r\}} \mathcal{L} = \int_0^x p(t)dt - C(q, e) + P[q - x] - h(r) + \mu(\bar{E} - e + r) \quad (18)$$

Importantly, the government takes into account the household and firm behavior and anticipates the impact of its policy choice on the market equilibrium, which can hence be expressed as

implicit functions of domestic emissions and removal quantities.

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial e} &= p(x) \frac{\partial x}{\partial e} - C_q \frac{\partial q}{\partial e} - C_e + P \left[\frac{\partial q}{\partial e} - \frac{\partial x}{\partial e} \right] + \frac{\partial P}{\partial e} [q - x] - \mu = 0 \\ \Leftrightarrow -C_e &= \mu - \underbrace{\frac{\partial P}{\partial e} [q - x]}_{:= \Omega}\end{aligned}\tag{19}$$

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial r} &= -h' + \mu = 0 \\ \Leftrightarrow h' &= \mu\end{aligned}\tag{20}$$

The unilateral optimality conditions deviate from the social planner solution if $\Omega := \frac{\partial P}{\partial e} [q - x] \neq 0$.

Proposition 1. *Given an exogenous net-emission target $\bar{E} \geq 0$ and perfect competition on the international market, the unilaterally optimal mix of abatement and removal in a large open economy satisfies*

$$\begin{aligned}-C_e - h' &= -\frac{\partial P}{\partial e} [q - x] \\ &= -\Omega\end{aligned}$$

where Ω is the terms-of-trade effect. The sign of Ω is ambiguous and depends on the trade balance.

Proof. Plugging (20) into (19) and rearranging yields the result. The second part follows from noting that $\frac{\partial P}{\partial e} < 0$. See Appendix B for the derivation of the comparative statics. \square

We see that unilaterally optimal emission and removal levels depart from the principle of equal marginal abatement and removal cost due to the *terms-of-trade effect* Ω .

If the trade balance is negative, the terms-of-trade effect is positive and the government increases the amount of removal relative to first best. In contrast, if the trade balance is positive, the terms-of-trade effect is negative and the government restricts the amount of removal relative to first best. In both cases, the rationale for altering the composition of abatement and removal to achieve the regional net-emission target is given by the motive of *tariff substitution* (see e.g., Copeland and Taylor, 2004; Phaneuf and Requate, 2016). In line with the literature on strategic environmental policy, the finding suggests that a net-exporting region has an incentive to increase the world market price to boost industry profits, while a net-importing region has an incentive to lower the world market price to increase domestic welfare. In the absence of

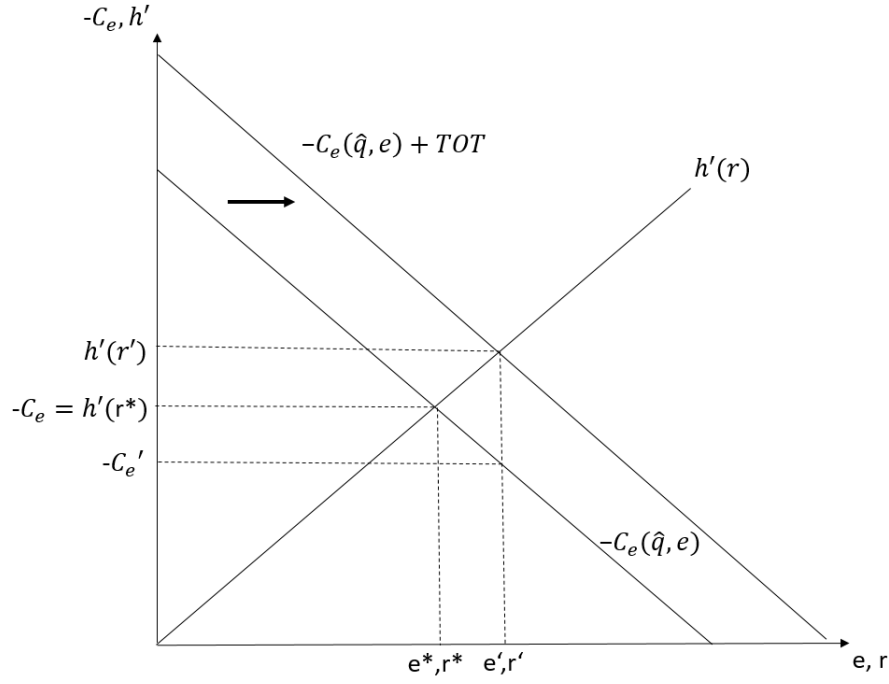


Figure 3: First-best residual emissions $\{e^*, r^*\}$ and unilaterally optimal residual emissions $\{e', r'\}$ in a net-importing region with a net-zero target.

other trade policy instruments (for example due to WTO rules), restricting or expanding the use of carbon removal can be used strategically by governments in order to influence the world market price. Interestingly, the possibility of carbon removal offers a new avenue for strategic environmental policy to substitute trade policy, even if a region needs to comply with an exogenous net-emission target. However, the direction of the terms-of-trade effect is ambiguous. Consequently, general warnings about the excessive use of carbon removal in net-emission targets for strategic trade considerations are not warranted if international markets are perfectly competitive.

An example of the terms-of-trade effect in an economy with a net-zero emission target is illustrated in Figure 3. In this example, the region is a net-importer. Hence, the terms-of-trade effect is positive and the government chooses a higher level of residual emissions than the social planner.

Imperfect Competition

Alternatively, assume imperfect competition on the international market. With Cournot quantity competition, the firms' first-order condition becomes

$$C_q = P'(Q)q + P(Q) \quad (21)$$

The government maximizes domestic welfare and anticipates the equilibrium behavior of firms on the international market. The associated first-order conditions are:

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial e} &= p(x) \frac{\partial x}{\partial e} - C_q \frac{\partial q}{\partial e} - C_e + P(Q) \left[\frac{\partial q}{\partial e} - \frac{\partial x}{\partial e} \right] + P'(Q) \left[\frac{\partial q}{\partial e} + \frac{\partial q^F}{\partial e} \right] [q - x] - \mu = 0 \\ \Leftrightarrow -C_e &= \mu + P'(Q)x \left(\frac{\partial q}{\partial e} + \frac{\partial q^F}{\partial e} \right) - P'(Q)q \frac{\partial q^F}{\partial e} \end{aligned} \quad (22)$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial r} &= -h' + \mu = 0 \\ \Leftrightarrow h' &= \mu \end{aligned} \quad (23)$$

Proposition 2. *Given an exogenous net-emission target $\bar{E} \geq 0$ and imperfect competition on the international market, the unilaterally optimal mix of abatement and removal in a large open economy satisfies*

$$\begin{aligned} -C_e - h' &= \underbrace{P'(Q) \left(\frac{\partial q}{\partial e} + \frac{\partial q^F}{\partial e} \right) x}_{\text{Imperfect competition effect}} - \underbrace{P'(Q) \frac{\partial q^F}{\partial e} q}_{\text{Rent shifting effect}} \end{aligned} \quad (24)$$

which implies $-C_e < h'$, $e > e^*$ and $r > r^*$.

Proof. Plugging (23) into (22) and rearranging yields (24). Noting that the first term on the right-hand-side of (24) is negative and the second term is positive, it follows that $-C_e < h'$. The claims about emission and removal quantities compared to first-best follow from the curvature of the cost functions given in Assumptions 1 and 2. \square

Under imperfect competition, we see that unilaterally optimal emission and removal levels depart from the principle of equal marginal abatement and removal cost due to the *imperfect competition effect* and the *rent shifting effect*. Both effects provide an incentive to decrease marginal abatement cost relative to marginal removal cost.

First, the *imperfect competition effect* arises due to the existing shortage of supply caused by imperfect competition on the international market. The government can counterbalance this shortage by requiring less abatement of domestic firms, thereby lowering marginal production cost and increasing domestic output. Second, the *rent shifting effect* represents the strategic incentive to allow the domestic industry to gain a larger market share on the international market. Due to lower marginal abatement cost, the domestic industry can commit to higher output levels and, in turn, rents are shifted from the foreign firm to the domestic firm. As the government strategically decreases abatement and increases removal relative to first-best,

this effect can be interpreted as *removal dumping*.³ Consequently, the possibility to remove emissions from the atmosphere creates an incentive to set "*weak net-emission targets*", where "*weak*" refers to setting marginal abatement cost below first-best levels.

3.5 Optimal unilateral carbon prices

In a decentralized economy, the unilaterally optimal quantities derived above can be implemented via carbon pricing. In particular, the government could charge a tax τ on emissions and pay a subsidy s on removals. The firm's maximization problem becomes

$$\max_{\{q, e, r\}} \pi(q, e, r) = Pq - C(q, e) - \tau e + sr - h(r) \quad (25)$$

which yields the optimality conditions

$$C_q = P \quad (26)$$

$$-C_e = \tau \quad (27)$$

$$h' = s \quad (28)$$

or (26)' $C_q = P'(Q)q + P(Q)$ in the case of imperfect competition. Proposition (3) summarizes the optimal carbon prices in both cases.

Proposition 3. *In the case of perfect competition (pc), the optimal carbon prices are given by*

$$\tau^{pc} = \mu^{pc} - \Omega \quad (29)$$

$$s^{pc} = \mu^{pc} \quad (30)$$

where μ^{pc} is the shadow price of the net-emission target under perfect competition and Ω is the terms-of-trade effect.

³In the literature on strategic environmental policy (e.g., Phaneuf and Requate, 2016), a similar effect is referred to as *environmental dumping* for the case of optimal unilateral carbon pricing under imperfect competition (without an exogenous net-emission target and carbon removal).

In the case of imperfect competition (ic), the optimal carbon prices are given by

$$\tau^{ic} = \mu^{ic} + P'(Q)x \left(\frac{\partial q}{\partial e} + \frac{\partial q^F}{\partial e} \right) - P'(Q)q \frac{\partial q^F}{\partial e} \quad (31)$$

$$s^{ic} = \mu^{ic} \quad (32)$$

where μ^{ic} is the shadow price of the net-emission target under imperfect competition.

Proof. Comparing the firm optimality conditions in (27) - (28) with the first-order conditions of the government in (19) - (20) and (22) - (23) yields the result. \square

We observe that the tax on emissions is adjusted for the *terms-of-trade effect* in the case of perfect competition and for the *imperfect competition effect* and the *rent shifting effect* in the case of imperfect competition. In contrast, the subsidy for removals is always set equal to the shadow price of the net-emission target. However, the shadow price for the government differs from the shadow price in the social planner problem, which implies that removal quantities differ from first-best.⁴

4 Optimal Unilateral Policy with Removal Trade

Instead of producing all removal domestically, it might be the case that region D needs to source removals on the international removal market at price Ψ . Removals are supplied by competitive firms with convex cost $h(R)$. The profit function of removal firms is given by $\pi(R) = \Psi R - h(R)$ and profit maximization yields

$$\Psi = h' \quad (33)$$

In equilibrium, the market-clearing price Ψ ensures that removal supply equals total demand for removals, that is, $R = r + r^F$.

Suppose now that region D owns a share $\lambda \in [0, 1]$ of the global removal market. The government in region D chooses emissions and removals to maximize domestic welfare and anticipates the equilibrium on both the international goods market and the market for removals. The government's constrained maximization problem becomes

$$\max_{\{e, r\}} W(e, r) = \int_0^x P(t)dt - C(q, e) + p[q - x] - \Psi r + \lambda \pi_R \quad (34)$$

⁴See Appendix C for an additional discussion of the shadow price of the net-emission target.

subject to

$$\bar{E} = e - r \quad (35)$$

$$\pi(R) = \Psi R - h(R) \quad (36)$$

$$\Psi = h' \quad (37)$$

$$r^F = \phi(r) \quad (38)$$

Most importantly, equation (38) describes the removal demand in region F as a function of removal in region D . The constrained optimization problem is

$$\begin{aligned} \max_{\{e, r\}} \mathcal{L} = & \int_0^x P(t)dt - C(q, e) + p[q - x] - h'(r + \phi(r))r \\ & + \lambda \left[h'(r + \phi(r))(r + \phi(r)) - h(r + \phi(r)) \right] + \mu(\bar{E} - e + r) \end{aligned} \quad (39)$$

Assuming perfect competition on international markets, the first-order conditions are

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial e} = & p(x) \frac{\partial x}{\partial e} - C_q \frac{\partial q}{\partial e} - C_e + P \left[\frac{\partial q}{\partial e} - \frac{\partial x}{\partial e} \right] + \frac{\partial P}{\partial e} [q - x] - \mu = 0 \\ \Leftrightarrow -C_e = & \underbrace{\mu - \frac{\partial P}{\partial e} [q - x]}_{\Omega} \end{aligned} \quad (40)$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial r} = & -h''(1 + \phi')r - h' + \lambda \left[h''(1 + \phi')(r + \phi(r)) \right] + \mu = 0 \\ \Leftrightarrow \Psi = & \underbrace{\mu + (1 + \phi')h''R \left[\lambda - \frac{r}{R} \right]}_{\Theta} \end{aligned} \quad (41)$$

which deviates from first best if $\Omega \neq 0$, $\Theta \neq 0$, or both.

Proposition 4. *Given an exogenous net-emission target $\bar{E} \geq 0$ and perfect competition on international markets, the unilaterally optimal mix of abatement and removal in a large open economy that owns the share $\lambda \in [0, 1]$ of global removal resources satisfies*

$$\begin{aligned} -C_e - \Psi = & -\frac{\partial P}{\partial e} [q - x] - (1 + \phi')h''R \left[\lambda - \frac{r}{R} \right] \\ = & -\Omega - \Theta \end{aligned} \quad (42)$$

where Ω is the terms-of-trade effect and Θ is the removal trade balance effect. The sign of Θ is ambiguous and depends on the removal trade balance.

Proof. Plugging (41) into (40) and rearranging yields the result. The second part follows from observing that $0 \leq (1 + \phi') \leq 1$ and $h'' > 0$. See Appendix B for a derivation of the comparative statics. \square

Proposition (4) states that unilaterally optimal emission and removal levels depart from the principle of equal marginal abatement and removal cost due to the familiar *terms-of-trade effect* Ω and the new *removal trade balance effect* Θ .

If the removal trade balance is negative, the share λ of region D in the removal market is smaller than its share in removal demand, that is $(\lambda - \frac{r}{R}) < 0$. In this case, the removal trade balance effect is negative and creates an incentive to decrease removal demand in region D . In contrast, if the removal trade balance is positive, the removal trade balance effect is positive and creates an incentive to increase the demand for carbon removal in region D . In both cases, the rationale for influencing domestic removal demand is to alter the world market price for removal in order to increase domestic welfare. *Ceteris paribus*, a net-removal-exporting region would increase removal demand relative to first-best to drive up the world market price, while a net-removal-importing region would decrease removal demand relative to first-best to lower the world market price.

However, both the *terms-of-trade effect* and the *removal trade balance effect* can lead to distortions in either direction, leading to an ambiguous net effect on the mix of abatement and removal in the net-emission target. Table 1 summarizes possible net-effects on the level of removal compared to first-best. For example, an importing country with large removal resources would find it optimal to increase removals to achieve the net-emission target. In contrast, an exporting country with small removal potential would decrease removal relative to first-best. In the case that the effects have opposite signs, the net effect is ambiguous and depends on the relative size of the distortions. However, given the current low levels of removal in most countries (Smith et al., 2023), it seems plausible that a policy relevant scenario is given in the first column, that is $\Theta \leq 0$. Thus, the removal trade balance effect will either be small or lead to a downward distortion of removal quantities in net-emission targets.

4.1 Policy instruments

The unilaterally optimal mix of abatement and removal can be achieved in three ways. First, a command-and-control type of regulation can set a cap on emissions equal to the unilaterally optimal amount and publicly procure removals on the international market until the optimality

Goods trade balance ($q - x$)	Removal trade balance ($\lambda - \frac{r}{R}$)		
	Importer $\Theta < 0$	Exporter $\Theta > 0$	Balanced trade $\Theta = 0$
Importer $\Omega > 0$	Ambiguous	Increasing $-C_e < h'$	Increasing $-C_e < h'$
Exporter $\Omega < 0$	Decreasing $-C_e > h'$	Ambiguous	Decreasing $-C_e > h'$
Balanced trade $\Omega = 0$	Decreasing $-C_e > h'$	Increasing $-C_e < h'$	—

Table 1: Net effect on removal in the unilaterally optimal mix of abatement and removal for a given net-emission target \bar{E} , relative to the social planner solution.

condition in (41) is satisfied. Second, a tax $\tau^* = \mu^* - \Omega^*$ could be levied on emissions and a subsidy $s^* = \mu^* + \Theta^*$ could be paid to private firms for any unit of removal purchased on the international market. A third option would be to impose a removal obligation on firms according to which they have to purchase a unit of removal for any unit of emissions that exceeds the net-emission target. In addition, the government could alter the relative cost of abatement and removal by charging a levy τ_e on emissions and an ad-valorem levy τ_r on the removal price. In this case, the firms optimization problem becomes

$$\max_{\{q, e\}} \pi(q, e) = pq - C(q, e) - \tau_e e - \Psi(1 + \tau_r)(e - \bar{E}) \quad (43)$$

with the optimality condition

$$-C_e = \tau_e + \Psi(1 + \tau_r) \quad (44)$$

Proposition (5) gives the optimal levies τ_e and τ_r that implement the unilateral optimal quantities.

Proposition 5. *In the case of perfect competition, international trade in removals and a removal obligation on domestic firms, the optimal levy τ_e on emissions and the optimal ad-*

valorem levy τ_r on removal purchases are given by

$$\tau_e^* = -\Omega \quad (45)$$

$$\tau_r^* = -\frac{\Theta}{\Psi} \quad (46)$$

where the emission levy internalizes the terms-of-trade effect Ω and the removal levy internalizes the removal trade balance effect Θ .

If no levy is charged on removal purchases ($\tau_r = 0$), the optimal levy on emissions internalizes both effects:

$$\tau_e^* = -(\Theta + \Omega) \quad (47)$$

Similarly, if no levy is charged on emissions ($\tau_e = 0$) the optimal removal levy becomes

$$\tau_r^* = -\frac{\Theta + \Omega}{\Psi} \quad (48)$$

Proof. Comparing (44) with (42) yields the result. \square

The removal obligation ensures that the net-emission target is met. The mix of abatement and removal at which the target is achieved can be influenced via the emission and removal levies. Note that depending on the sign of Ω and Θ , both levies could either be a tax or a subsidy. As due to the removal obligation removal is a direct function of emissions, the unilaterally optimal allocation can also be achieved with a single levy on either emissions or removals. In this case, the levy internalizes the net-effect of the *terms-of-trade effect* and *removal trade balance effect*.

5 Flexible and Fixed Net-Emission Targets

Finally, an interesting observation concerns the *type* net-emission targets in the foreign region. With a *fixed* net-emission target, the government would allocate a fixed budget \bar{e}^F to the polluting industry and ensure the provision of a fixed amount of removal \bar{r}^F . In contrast, a *flexible* net-emission target would entail a regulation that allows the mix of abatement and removals to adapt to changing market conditions. Such a regulation could be, for example, a removal obligation for firms.

Interestingly, the type of net-emission target in the foreign region has an influence on the incentive for strategic environmental policy in the domestic region. In general, a fixed net-emission target makes the reaction of foreign firms to changing world market prices less pronounced compared to the flexible policy regime. This "softened" response has two implications.

First, a fixed net-emission target in region F increases the size of the *removal trade balance effect* Θ compared to a flexible regulation. With a fixed net-emission target, removal demand in region F is inelastic. The inelastic demand implies that $\phi' = 0$, which in turn implies an increase in Θ according to equation (41). Recall that for net removal exporters there is an incentive to subsidize removal to increase the world market price for removals. This incentive becomes stronger because foreign demand does not decrease in response to the price increase. Similarly, for net removal importers the incentive to tax domestic removal demand is stronger because foreign demand does not increase in response to the price decrease. In sum, a fixed net-emission target in region F makes the domestic government's intervention on the removal market more effective and increases the incentive for strategic behavior on the removal market. Second, a fixed target for abatement and removal also increases the size of the *terms-of-trade effect* Ω . Suppose first that the domestic government's policy choice increases the world market price for the consumption good. In this case, the foreign firms respond to the price increase by expanding production. With the increase in production, the firms would find it optimal to increase emissions to lower marginal abatement cost.⁵ However, due to the fixed net-emission target in region F , emissions cannot be upwardly adjusted and hence each unit of output needs to be produced with a lower emission intensity, rendering production more expensive. In contrast, a flexible net-emission target allows firms to increase their emissions until marginal abatement cost are again equal to marginal removal cost. Consequently, the quantity reaction of foreign firms in response to a price increase is smaller if the foreign region imposes a fixed net-emission target. Therefore, a fixed net-emission target increases the *terms-of-trade effect* for exporting regions.

An analogous mechanism increases the *terms-of-trade effect* for importing regions that aim to lower the world market price. A decrease of the world market price leads to a decrease in production in F . With a fixed net-emission target, the foreign firms can now produce fewer goods at a higher emission intensity, thereby lowering marginal abatement cost and the marginal cost of production. Put differently, compliance with the net-emission target becomes less burdensome for lower levels of production, which lowers the cost of production. In contrast, a flexible

⁵Recall that $C_{qe} < 0$ and $-C_{eq} > 0$ for all $e < \hat{e}^q$.

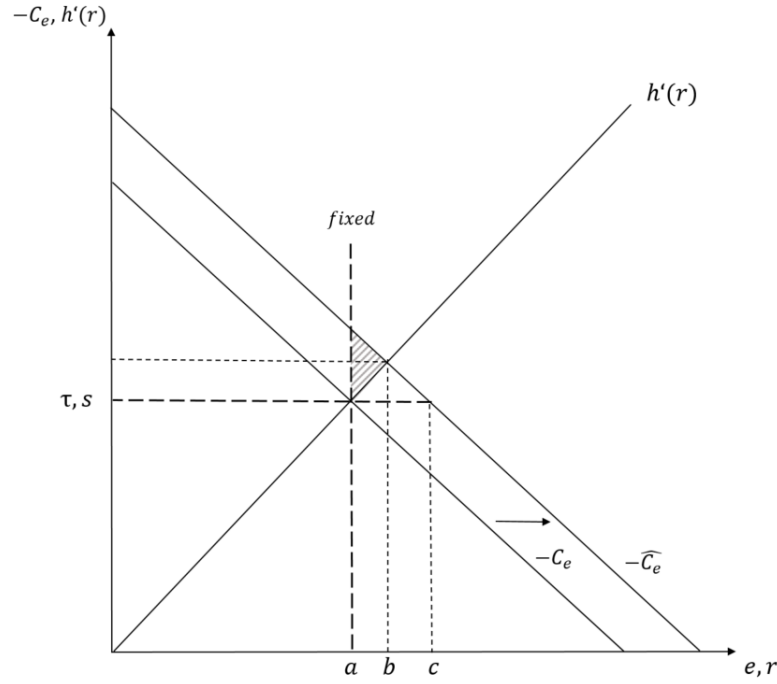


Figure 4: Residual emissions in region F after a positive price shock on the product market. With a fixed net-emission target, residual emissions are inefficiently low ($a < b$), resulting in a deadweight loss given by the shaded area. With carbon pricing, the ex-post mix of emissions (c) and removal (a) fails to meet the target ($c - a > \bar{E} = 0$). With a flexible net-zero target implemented by a removal obligation, the mix of abatement and removal after the shock remains efficient (b).

net-emission target forces foreign firms to decrease their level of emissions such that marginal abatement cost equal marginal removal cost. It follows that a flexible net-emission target leads to a stronger decrease in production in response to a negative price shock than a fixed net-emission target. Consequently, a fixed net-emission target in the foreign region renders the policy intervention by the domestic region more effective and increases the *terms-of-trade effect*.

Finally, note that from the perspective of the foreign region, the flexible target is preferable because a fixed mix of removal and abatement introduces inefficiencies if market conditions change. This inefficiency is illustrated in Figure 4. In this example, the strategic behavior by the domestic government causes a price increase on the product market, leading to an increase in production in F and to an upward shift of the marginal abatement cost schedule. Efficiency would require an increase in residual emissions from (a) to (b), which is prevented by the fixed target. The resulting inefficiency is given by the shaded area.

Moreover, it is noteworthy that while a carbon pricing regime (tax on emissions and subsidy for removal) can implement the ex-ante optimal allocation, any change in market conditions causes the foreign region to miss its net-emission target ex-post. In the example in Figure 4, a tax-

subsidy scheme calibrated to achieve the ex-ante optimal allocation (a) fails to meet the target after the price shock. In this case, foreign firms pollute more while removal is held constant, causing the foreign region to exceed its target. In contrast, a negative price shock would cause the foreign country to overachieve its target. Therefore, relying solely on price instruments to achieve a net-emission target seems not to be a viable policy option. Instead, a removal obligation that requires firms to offset each unit of emissions that exceeds the net-emission target can achieve the ex-post efficient mix of abatement and removal.

6 Conclusion

This paper has analyzed the strategic use of residual emissions in net-emission targets. The key results from the literature on strategic environmental policy carry over to the case of exogenous net-emission targets with carbon removal. First, the *terms-of-trade effect* can lead exporters to decrease residual emissions to drive up world market prices, while the reverse is the case for importers. With imperfect competition, the *rent-shifting effect* unambiguously increases residual emissions for both importers and exporters. This practice of strategically increasing the use of carbon removal to boost industry profits might be referred to as *removal dumping*. Second, the new *removal trade balance effect* drives up residual emissions for removal exporters to increase removal prices, while the reverse is true for removal importers. Overall, the finding that strategic considerations increase residual emissions and lead to "weak" net-emission targets is not robust, as the direction of the distortion depends on the assumed market structure and the trade balance on the goods and removal markets. However, if strategic considerations in the choice of residual emissions are present, they are always stronger if the foreign region has a fixed net-emission target instead of a flexible net-emission target.

Future research could build on the modeling approach and findings presented in this paper. First, if the domestic region has an incentive to behave strategically, so does the foreign region. An analysis of the resulting Nash equilibrium and associated removal quantities might yield relevant insights for the design of international agreements on carbon removal. Second, this paper has assumed that carbon removal does not change the marginal cost of production. However, large-scale removal might compete for input factors like energy with the industry. Hence, future versions of this paper could analyze the resulting trade-offs for policymakers. Finally, it would be interesting to estimate the size of the distortion introduced by strategic behavior. This could be done using a calibrated quantitative trade model.

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Appendix

A Global net-emission target

If the social planner maximizes global welfare subject to a *global* net-zero target, i.e. $e + e_f = r + r_f$, the maximization problem would be the following:

$$\max_{\{x_i, q_i, e_i, r_i\}} \mathcal{L} = W(q, x, e, r) + W^f(q_f, x_f, e_f, r_f) + \psi[e + e_f - r - r_f] \quad (49)$$

where ψ is the shadow price of the global net-zero constraint. The first-order conditions are

$$\frac{\partial \mathcal{L}}{\partial x_i} = 0 \quad \Longleftrightarrow \quad P_i(x_i) = p \quad (50)$$

$$\frac{\partial \mathcal{L}}{\partial q_i} = 0 \quad \Longleftrightarrow \quad C_{q_i}^i = p \quad (51)$$

$$\frac{\partial \mathcal{L}}{\partial e_i} = 0 \quad \Longleftrightarrow \quad -C_{e_i}^i = -\psi \quad (52)$$

$$\frac{\partial \mathcal{L}}{\partial r_i} = 0 \quad \Longleftrightarrow \quad h_i'(r_i) = -\psi \quad (53)$$

It follows from (52) and (53) that the optimal mix of abatement and removal is such that marginal abatement and removal cost are equalized *across* countries, i.e. it holds that $-C_e = -C_{e_f}^f = h'(r) = h_f'(r_f)$. This result implies that the social planner exploits heterogeneity in the production of output and removals and allocates removals from one country for compensating emissions in another country.

B Comparative Statics

To derive the comparative statics for the endogenous variables (x, x_f, q, q_f, e_f, P) we need to assume how emissions and removals are regulated in the foreign region. In the following, we assume a *flexible net-emission target* in the foreign region that is implemented via a removal obligation. That is, foreign firms need to remove each ton of emissions that they emit in exceedance of the net-emission target. For ease of exposition, assume $\bar{E}_f = 0$.

The market equilibrium in the case of a unilateral command-and-control policy in region D is characterized by the following equations:

Households' utility maximization

$$p(x) = P \quad (54)$$

$$p_f(x_f) = P \quad (55)$$

Firms' profit maximization

$$C_q(q, e) = P \quad (56)$$

$$C_q^f(q_f, e_f) = P \quad (57)$$

$$-C_e(q, e) = \max(0, -C_e(q, \bar{e})) \quad (58)$$

$$-C_e^f(q_f, e_f) = h'_f(e_f) \quad (59)$$

$$h'(r) = h'(\bar{r}) \quad (60)$$

Market clearing

$$x + x_f = q + q_f \quad (61)$$

Assuming that the domestic emission cap is always binding, we can differentiate the equation system (54) - (61) with respect to the domestic emissions cap \bar{e} .

$$p'(x) \frac{\partial x}{\partial \bar{e}} = \frac{\partial P}{\partial \bar{e}} \quad (62)$$

$$p'_f(x_f) \frac{\partial x_f}{\partial \bar{e}} = \frac{\partial P}{\partial \bar{e}} \quad (63)$$

$$C_{qq}(q, \bar{e}) \frac{\partial q}{\partial \bar{e}} + C_{qe}(q, \bar{e}) = \frac{\partial P}{\partial \bar{e}} \quad (64)$$

$$C_{qq}^f(q_f, e_f) \frac{\partial q_f}{\partial \bar{e}} + C_{qe}^f(q_f, e_f) \frac{\partial e_f}{\partial \bar{e}} = \frac{\partial P}{\partial \bar{e}} \quad (65)$$

$$-C_{ee}^f(q_f, e_f) \frac{\partial e_f}{\partial \bar{e}} - C_{eq}^f(q_f, e_f) \frac{\partial q_f}{\partial \bar{e}} = h''_f(e_f) \frac{\partial e_f}{\partial \bar{e}} \quad (66)$$

$$\frac{\partial x}{\partial \bar{e}} + \frac{\partial x_f}{\partial \bar{e}} = \frac{\partial q}{\partial \bar{e}} + \frac{\partial q_f}{\partial \bar{e}} \quad (67)$$

The system of equations can be rewritten in the matrix form $Ma = b$, with

$$a' = \begin{pmatrix} \frac{\partial x}{\partial \bar{e}} & \frac{\partial x_f}{\partial \bar{e}} & \frac{\partial q}{\partial \bar{e}} & \frac{\partial q_f}{\partial \bar{e}} & \frac{\partial e_f}{\partial \bar{e}} & \frac{\partial P}{\partial \bar{e}} \end{pmatrix}$$

$$b' = \begin{pmatrix} 0 & 0 & -C_{qe} & 0 & 0 & 0 \end{pmatrix}$$

$$M = \begin{bmatrix} p'(x) & 0 & 0 & 0 & 0 & -1 \\ 0 & p'_f(x_f) & 0 & 0 & 0 & -1 \\ 0 & 0 & C_{qq} & 0 & 0 & -1 \\ 0 & 0 & 0 & C_{qq}^f & C_{qe}^f & -1 \\ 0 & 0 & 0 & -C_{eq}^f & -C_{ee}^f - h_f'' & 0 \\ 1 & 1 & -1 & -1 & 0 & 0 \end{bmatrix}$$

Multiplying both sides of $Ma = b$ with the inverse of matrix M and denoting the Hessian of the cost function in the foreign region by $H^f[C_f] = C_{ee}^f C_{qq}^f - (C_{eq}^f)^2 > 0$ yields expressions for the comparative statics.

$$\frac{\partial x}{\partial \bar{e}} = \frac{C_{qe} p'_f (C_{qq}^f h_f'' + H^f[C_f])}{\det(M)} \quad (68)$$

$$\frac{\partial x_f}{\partial \bar{e}} = \frac{C_{qe} p' (C_{qq}^f h_f'' + H^f[C_f])}{\det(M)} \quad (69)$$

$$\frac{\partial q}{\partial \bar{e}} = \frac{C_{qe} \left(p'_f (C_{qq}^f h_f'' + H^f[C_f]) - p' (p'_f (C_{ee}^f + h_f'') - C_{qq}^f h_f'' - H^f[C_f]) \right)}{\det(M)} \quad (70)$$

$$\frac{\partial q_f}{\partial \bar{e}} = \frac{C_{qe} p'_f (C_{ee}^f + h_f'')}{\det(M)} \quad (71)$$

$$\frac{\partial e_f}{\partial \bar{e}} = -\frac{C_{eq}^f C_{qe} p'_f}{\det(M)} \quad (72)$$

$$\frac{\partial P}{\partial \bar{e}} = \frac{C_{qe} p'_f (C_{qq}^f h_f'' + H^f[C_f])}{\det(M)} \quad (73)$$

Using the assumptions about the curvature of the utility and cost functions and noting that

$\det(M) > 0$, we can infer the sign of the expressions.

$$\begin{array}{ll} \frac{\partial x}{\partial \bar{e}} > 0 & \frac{\partial x_f}{\partial \bar{e}} > 0 \\ \frac{\partial q}{\partial \bar{e}} > 0 & \frac{\partial q_f}{\partial \bar{e}} < 0 \\ \frac{\partial e_f}{\partial \bar{e}} < 0 & \frac{\partial P}{\partial \bar{e}} < 0 \end{array}$$

□

The derivations of the comparative statics for imperfect competition and international trade in removals follow the same procedure and are not repeated here.

B.1 Trade in Removals

This subsection shows that for sufficiently symmetric regions, the results described in the main text hold. In addition, I discuss the ambiguity about prices for goods and removals in the case of asymmetric countries.

The system of equations can be rewritten in the matrix form $Ma = b$, with

$$a' = \left(\frac{\partial x}{\partial \bar{e}} \quad \frac{\partial x_f}{\partial \bar{e}} \quad \frac{\partial q}{\partial \bar{e}} \quad \frac{\partial q_f}{\partial \bar{e}} \quad \frac{\partial e_f}{\partial \bar{e}} \quad \frac{\partial P}{\partial \bar{e}} \quad \frac{\partial \Psi}{\partial \bar{e}} \quad \frac{\partial R}{\partial \bar{e}} \right)$$

$$b' = \left(0 \quad 0 \quad -C_{qe} \quad 0 \quad 0 \quad 0 \quad 0 \quad -1 \right)$$

$$M = \begin{bmatrix} p'(x) & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & p'_f(x_f) & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & C_{qq} & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & C_{qq}^f & C_{qe}^f & -1 & 0 & 0 \\ 0 & 0 & 0 & -C_{eq}^f & -C_{ee}^f & 0 & -1 & 0 \\ 1 & 1 & -1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & h'' \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 \end{bmatrix}$$

Multiplying both sides of $Ma = b$ with the inverse of matrix M yields expressions for the comparative statics. The determinant of M is given by

$$\det(M) = (p' + p'_f) (-C_{qq}H^f[C_f] - C_{qq}^f C_{qq} h'') + p' p'_f (C_{qq} C_{ee}^f + H^f[C_f] + (C_{qq} + C_{qq}^f) h'') > 0$$

which is positive by inspection. Assuming that firms in both regions are sufficiently symmetric, that is, they have linear marginal cost with the same slope ($C_{qq} = C_{qq}^f, C_{qe} = C_{qe}^f, C_{ee} = C_{ee}^f$),

we find the following comparative statics.

$$\frac{\partial x}{\partial \bar{e}} = \frac{C_{qe}H[C]p'_f}{\det(M)} \quad (74)$$

$$\frac{\partial x_f}{\partial \bar{e}} = \frac{C_{qe}H[C]p'}{\det(M)} \quad (75)$$

$$\frac{\partial q}{\partial \bar{e}} = p'_f p'_f \left(-\frac{C_{ee}C_{qe}}{\det(M)} - \frac{2C_{qe}h''}{\det(M)} \right) + \frac{C_{qe}C_{qq}h''(p' + p'_f)}{\det(M)} + \frac{C_{qe}H[C](p' + p'_f)}{\det(M)} \quad (76)$$

$$\frac{\partial q_f}{\partial \bar{e}} = p'_f p'_f \left(\frac{C_{ee}C_{qe}}{\det(M)} + \frac{2C_{qe}h''}{\det(M)} \right) - \frac{C_{qe}C_{qq}h''(p' + p'_f)}{\det(M)} \quad (77)$$

$$\frac{\partial e_f}{\partial \bar{e}} = p'_f p'_f \left(-\frac{C_{qe}^2}{\det(M)} - \frac{2C_{qq}h''}{\det(M)} \right) + \frac{C_{qq}^2 h''(p' + p'_f)}{\det(M)} \quad (78)$$

$$\frac{\partial P}{\partial \bar{e}} = \frac{C_{qe}H[C]p'_f p'_f}{\det(M)} \quad (79)$$

$$\frac{\partial \Psi}{\partial \bar{e}} = \frac{2H[C]h''p'_f p'_f}{\det(M)} - \frac{C_{qq}H[C]h''(p' + p'_f)}{\det(M)} \quad (80)$$

$$\frac{\partial R}{\partial \bar{e}} = \frac{2H[C]p'_f p'_f}{\det(M)} - \frac{C_{qq}H[C](p' + p'_f)}{\det(M)} \quad (81)$$

This implies the following signs

$$\begin{array}{ll} \frac{\partial x}{\partial \bar{e}} > 0 & \frac{\partial x_f}{\partial \bar{e}} > 0 \\ \frac{\partial q}{\partial \bar{e}} > 0 & \frac{\partial q_f}{\partial \bar{e}} < 0 \\ \frac{\partial e_f}{\partial \bar{e}} < 0 & \frac{\partial P}{\partial \bar{e}} < 0 \\ \frac{\partial \Psi}{\partial \bar{e}} > 0 & \frac{\partial R}{\partial \bar{e}} > 0 \end{array}$$

□

Furthermore, note that $\frac{\partial \phi}{\partial \bar{e}} = \frac{\partial e_f}{\partial \bar{e}} < 0$. It can be shown that $(\frac{\partial e_f}{\partial \bar{e}} + 1) > 0$, which verifies the claim that $0 < (1 + \phi') < 1$.

C Shadow price of the net-emission target

The shadow price μ associated with a given net-emission target \bar{E} measures the marginal cost at which the target is achieved. Put differently, the shadow price measures by how much

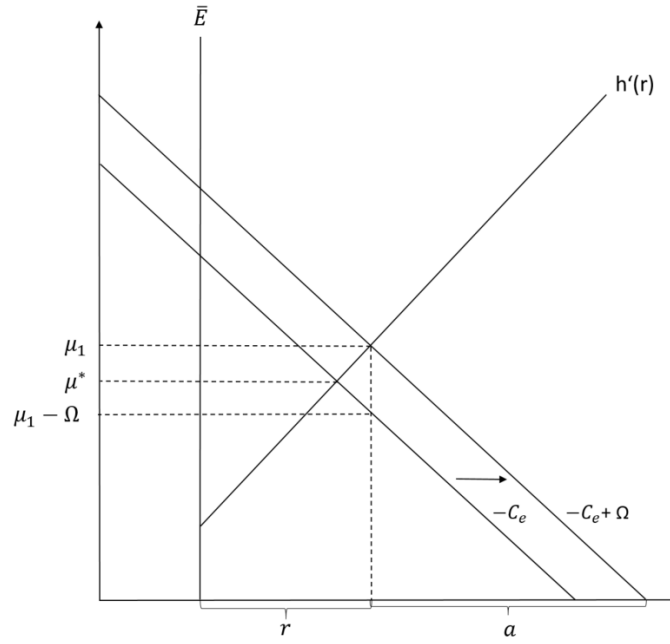


Figure C.1: Shadow prices for achieving the net-emission target \bar{E} in the social optimum (μ^*) and with optimal unilateral policy under perfect competition (μ_1) for a net-importing region.

domestic welfare would change if the net-emission target was relaxed by one unit. In this model, this is equal to the value of emitting one additional unit of emissions at zero cost, which is equal to the saved marginal abatement cost, net of any secondary effects that are captured by the additional terms introduced in section 3.3.

Figure C.1 shows that the shadow price for the government differs from the shadow price for the social planner. While for the social planner the marginal cost of achieving the net-emission target are given by μ^* , the government achieves the target at marginal cost μ_1 . In this example, the private marginal cost of emission reductions in the domestic region are given by the marginal abatement cost $-C_e$, net of the terms-of-trade effect Ω .

D Derivations

D.1 Terms of trade effect

$$\max_{\{e, r\}} \mathcal{L} = \int_0^x p(t)dt - C(q, e) + P[q - x] - h(r) + \mu(\bar{E} - e + r) \quad (82)$$

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial e} &= p \frac{\partial x}{\partial e} - C_q \frac{\partial q}{\partial e} - C_e + \frac{\partial P}{\partial e} [q - x] + P \left[\frac{\partial q}{\partial e} - \frac{\partial x}{\partial e} \right] - \mu = 0 \\
&= P \frac{\partial x}{\partial e} - P \frac{\partial q}{\partial e} - C_e + \frac{\partial P}{\partial e} [q - x] + P \frac{\partial q}{\partial e} - P \frac{\partial x}{\partial e} - \mu = 0 \\
&= -C_e + \frac{\partial P}{\partial e} [q - x] - \mu = 0
\end{aligned} \tag{83}$$

$$\frac{\partial \mathcal{L}}{\partial r} = -h' + \mu = 0 \tag{84}$$

where we have used the fact that $C_q = P$ from the firm optimization problem and $p(x) = P$ from the household's utility maximization.

D.2 Removal trade balance effect

$$\begin{aligned}
\max_{\{e, r\}} \mathcal{L} &= \int_0^x P(t) dt - C(q, e) + p[q - x] - h'(r + \phi(r))r \\
&\quad + \lambda [h'(r + \phi(r))(r + \phi(r)) - h(r + \phi(r))] + \mu(\bar{E} - e + r)
\end{aligned} \tag{85}$$

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial e} &= p \frac{\partial x}{\partial e} - C_q \frac{\partial q}{\partial e} - C_e + \frac{\partial P}{\partial e} [q - x] + P \left[\frac{\partial q}{\partial e} - \frac{\partial x}{\partial e} \right] - \mu = 0 \\
&= P \frac{\partial x}{\partial e} - P \frac{\partial q}{\partial e} - C_e + \frac{\partial P}{\partial e} [q - x] + P \frac{\partial q}{\partial e} - P \frac{\partial x}{\partial e} - \mu = 0 \\
&= -C_e + \frac{\partial P}{\partial e} [q - x] - \mu = 0
\end{aligned} \tag{86}$$

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial r} &= -h''(1 + \phi')r + h' \\
&\quad + \lambda [h''(1 + \phi')(r + \phi(r)) + h'(1 + \phi') - h'(1 + \phi')] + \mu = 0 \\
&= -h''(1 + \phi')r + h' + \lambda [h''(1 + \phi')(r + \phi(r))] + \mu = 0 \\
&= -h''(1 + \phi')r + h' + \lambda [h''(1 + \phi')R] + \mu = 0 \\
&= h' + h''(1 + \phi')(\lambda R - r) + \mu = 0 \\
&= h' + h''(1 + \phi')R(\lambda - \frac{r}{R}) + \mu = 0
\end{aligned} \tag{87}$$

where we have used the fact that $C_q = P$ from the firm optimization problem and $p(x) = P$ from the household's utility maximization.