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General Oligopolistic Equilibrium: Strategic Firm Behaviour and Environmental Policy

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General Oligopolistic Equilibrium: Strategic Firm Behaviour and Environmental Policy *

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Abstract

This paper develops a GOLE model in the spirit of Neary and Tharakan (2012) to analyze the impact of a unilateral environmental policy reform on emission leakage, incorporating trade dynamics, oligopolistic competition, and capital-intensive abatement. The model builds on the strategic mechanism of Kreps and Scheinkman (1983): firms decide on up-front abatement investments in a first stage, which shape their production cost structures, emission intensities, and ultimately their mode of competition (Bertrand or Cournot) in the second stage. The analysis shows that raising the emission tax in one country increases the share of sectors investing in abatement, thereby significantly reducing emissions both domestically and abroad. Calibrated simulations reveal a *negative* leakage rate of about 80%, indicating substantial cross-border emission reductions. These reductions are driven primarily by the extensive margin, as additional sectors adopt abatement in response to the reform. At the same time, the unilateral reform entails a downside by increasing oligopolization and reducing competitiveness: global emission reductions come at the cost of weaker competition and lower consumer welfare.

JEL codes: F12, F15, F18

Keywords: General Oligopolistic Equilibrium, Strategic Firm Behaviour, Trade Liberalization, Trade and Environment, Abatement

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1 Introduction

With global warming, there is an urgent need for designing and implementing policies that cut down carbon emissions. However, there are concerns around environmental action, especially if governments unilaterally implement policies. One key concern is emission leakage (cf. Felder and Rutherford, 1993; Babiker, 2005), being the outflow of emissions from a reforming country towards a non-reforming country, thereby effectively undermining the reforming country's unilateral policy action. Social costs in terms of declines in production and welfare losses are one other important dimension of concern (cf. Pethig, 1976; Jaffe et al., 1995; Chen and Nie, 2016).

This paper builds a model to quantitatively analyze the effectiveness of unilateral environmental actions. To derive key features for the model framework, I emphasize some stylized facts on emission-intensive sectors (EIS): Firstly, emission-intensive sectors are particularly open to international trade, exposing them to international competition through the export of goods to each other's markets (Copeland et al., 2022). Secondly, emission-intensive sectors are characterized by relatively high degrees of market concentration. Data on the HHI Index for the United Kingdom shows considerable concentration in energy-intensive sectors of coke, chemicals, non-metallic minerals and basic metals (BEIS, 2023). Additionally, Andrew (2018) provides evidence on the CR4 Index for the US cement industry. Cludius et al. (2020) highlights imperfections in cost pass-throughs for chemicals and steel. Competition in EIS sectors can thus be perceived to take place between relatively few firms, interacting strategically against each other. Thirdly, emisison-intensive sectors are particularly capital-intensive (Yang and Shi, 2018). In light of existing environmental regulations, a large part of capital investment accrues to pollution abatement technology. In trade models, abatement efforts are usually modelled as a constant cost share of labor being diverted from production Copeland and Taylor (1994). Contrary to this, Forslid et al. (2018) empirically highlight a fixed cost component in abatement efforts of Swedish firms. An abatement plant, being a long-term asset, requires a large volume of capital expenditure at an initial stage. Furthermore, an abatement plant is subject to a fixed maximum production capacity, contrasting the notion of a completely variable input share. Hence, this model features abatement as a first-stage capital investment determining (labor-and emissions-intensive) production costs in the second stage.

Thus, this paper seeks to identify the effects of unilateral environmental action on emission leakage, accounting for trade, oligopolistic interaction and a first-stage, capital-intensive abatement investment. Addressing this question, the model expands on a so-called GOLE-framework

(Neary and Tharakan, 2012), being a trade model of oligopolistic competition in general equilibrium. Adding the environmental perspective, the framework is extended by emisisons-intensive production. Furthermore, the setting incorporates an emission abatement investment possibility that closely mirrors the capacity-investment mechanism of Kreps and Scheinkman (1983): In a first stage, firms have the option to invest in abatement, in a second stage, they generate output. The decison on abatement in stage one leads to a sectoral self-selection into either Bertrand or Cournot competition in stage two. Building on Neary and Tharakan (2012), the mode of competition is endogenized, reacting to changes in exogenous parameters, such as the emission tax rate. In a North-North setting of two initially symmetric countries, the unilateral policy reform removes symmetry between countries, raising the emission tax rate in the reforming country.

The rise in the reforming country‘s emission tax increases the share of sectors that invest in emission abatement in the international economy. As a result, emission levels strongly decrease in both countries. Furthermore, the increase in sectors investing in abatement translates into an increase in the number of Cournot sectors relative to Bertrand Sectors in the economy. This implies a trade-off between desirable effects in terms of emission reduction and undesirable outcomes in the context of oligopolization and decreased competitiveness.

Decomposing the effect on emissions in the two countries reveals that most of the reduction in emissions can be linked to the *extensive margin*: As additional sectors start investing in abatement, emissions fall at an equal rate across both countries. This constitutes a novel channel to the existing set of literature around trade , leakage and oligopolistic interaction. Additionally, the decline in emissions is reinforced by profit-maximizing output responses at the firm-level. This *intensive-margin* effect has been highlighted by Baccianti and Schenker (2022). Notably, in contrast to Melitz-style models with constant mark-ups (Egger et al., 2021), the role of across country wage rate spillover effects shows to be negligible in this setting. A calibrated simulation arrives at a *negative* leakage rate of around 80%, implying that almost the entire emission reduction achieved in the reforming country also spills over to the non-reforming country.

The literature on environmental policy, trade in final goods, and leakage yields significantly different outcomes regarding the effectiveness of a unilateral increase in emission taxes. CGE models typically find a large positive emission leakage rate as a response to unilateral environmental policy actions, mostly around 30% (Babiker, 2005; Böhringer et al., 2010; Fischer and Fox, 2012; Carbone and Rivers, 2017). However, policy-induced outflows of emissions have not been identified in most of the empirical literature (Aichele and Felbermayr, 2015; Naegele and Zaklan, 2019; Dechezleprêtre et al., 2022). Most recently, Colmer et al. (2024) outline that the

first stage of the EU ETS (from 2005 to 2012) cut emissions by around 16% without finding notable evidence for pollution relocation away from the European Union. More in line with this evidence, Melitz-style trade models with exporting and constant mark-ups find do not show emission relocations to non-reforming countries (Balistreri and Rutherford, 2012; Shapiro and Walker, 2018).[1] In particular, Egger et al. (2021) even find *negative* leakage, i.e. reductions of emissions in the non-reforming country caused by the reforming country's unilateral action. However, their results are mainly driven by general equilibrium spillovers to the non-reforming country's wage rate. Using an abatement technology à la Copeland and Taylor (1994), this mechanically translates into larger abatement investments. Such wage rate spillovers are estimated to be small from an empirical perspective. To the best of my knowledge, there is only one contribution that analyzes leakage in the context of variable mark-ups and oligopolistic interaction in general equilibrium. In a setting of Cournot competition, Baccianti and Schenker (2022) show that firms in the non-reforming country give a profit-maximizing response by raising mark-ups but reducing output volumes.This yields an emission reduction in the non-reforming country that is largely driven by the *intensive margin*. Their simulation results in a negative leakage rate of around 10%. As the next sections will outline, this model framework's multi-stage capital-intensive abatement technology enables an additional *extensive margin* effect, driven by the endogenous self-selection of sectors into abatement investment and modes of competition.

The remainder is structured as follows: Section 2 outlines the model setup. Section 3 presents the model calibration and provides numerical results for firm margins, output levels, emissions and welfare. Section 4 concludes.

2 Model Setup

2.1 Firm Costs

Firms in the international economy operate in a continuum of sectors along unit interval $z \in (0, 1)$. In each sector, firms compete in a free trade duopoly where one home firm competes against one foreign firm. For simplicity, exporting to the other country is tariff-free and not subject to any transport costs. Thus, firms charge the same price both for selling on their domestic market as well as for exporting. The two countries are fully symmetric (North-North)

[1] The mode of globalization featured in the model framework greatly matters for the results on leakage. Featuring offshoring (intermediate goods trading) instead of exporting in a Melitz-style framework with monopolistic competition, Bolz et al. (2024) arrive at positive leakage rates, possibly even above 100% in scenarios of initially high trade freeness.

prior to a unilateral environmental policy reform. The home country is considered to be the reforming country, indexed by i, while the foreign country is referred to as the non-reforming country, indexed by j. For simplicity and due to symmetry prior to the reform, only country i will be outlined in this section.

In analogy to Kreps and Scheinkman (1983), firms in each sector interact in two stages: In a first stage, firms in each sector have the possibility to invest in abatement $\xi(z)$, using δ units of capital.[2]. In country i, each unit of capital K_i employed for investing in abatement is to be renumerated with the economy-wide rental rate r_i. In the second stage, firms generate output $q(z)$, using γ units of labor l. Each worker is paid the economy-wide wage rate w_i.

If production in the second stage exceeds the scope of abatement investment in the first stage, a firm incurs some kind of a penalty (Maggi, 1996): It must switch on an additional, polluting production plant. This plant uses θ units of labor and emission-intensive fossil fuel e, the latter being priced with an emission tax t_i.[3] While the factor prices r_i and w_i adjust endogenously in general equilibrium, the emission tax t_i is set exogenously by the policy-maker. Hence, firms of country i are subject to the following structure:

$$C_i(z) = r_i\,\delta\,\xi(z) + \begin{cases} w_i\,\gamma\,q(z) & \text{if } q(z) \leq \xi(z) \\ w_i\,\gamma\,q(z) + (w_i + t_i)\;\theta(z)\;\left[q(z) - \xi(z)\right] & \text{if } q(z) > \xi(z) \end{cases} \tag{1}$$

,

where input requirements δ and γ are exogenous and set uniformly across sectors. In contrast to that, the penalty input requirement θ varies across the sector interval, so that $\theta'(z) > 0$ holds. Thus, it is relatively cheap to switch on the additional, polluting plant in sectors with z close to zero and relatively expensive in sectors with z close to one.

Marginal costs for output *within* abatement level and *above* abatement level can thus be derived as follows:

$$c_i^A = r_i\,\delta_i + w_i\,\gamma_i \qquad \text{and} \qquad c_i^N(z) = w_i\,\gamma_i + (w_i + t_i)\,\theta(z). \tag{2}$$

If output is within the scope of abatement investment, marginal costs in country i are denoted by c_i^A, comprising the sum of capital costs for abatement investment and labor costs for production *without* the additional, polluting plant. In the other case, output in stage two exceeds the scope

[2] Neary and Tharakan (2012) present production capacity investment as skilled-labor-intensive. Due to the capital intensity of abatement investment, I chose to connect abatement investments to the use of capital instead.

[3] Input requirements δ, γ θ are assumed to be identical across countries. Thus, indices are omitted.

of abatement investment set in stage one. Then, marginal costs are denoted by c_i^N as the sum of labor costs for production *without* the additional plant as well as labor and emissions costs for production *with* the additional plant. Firms in which sectors choose to invest in abatement? Deriving a trade-off condition determines firm-level abatement choice in each sector:

$$r_i\,\delta = (w_i + t_i)\,\theta(\tilde{z}). \tag{3}$$

Marginal (capital) costs of abatement investment on the left side stand against marginal (labor and emission) benefits of abatement investment on the right side. As θ increases as z moves from 0 to 1, I follow Neary and Tharakan (2012), highlighting a threshold sector $\tilde{z}$ beyond which the marginal benefit of abatement investment exceeds marginal cost of abatement investment. Hence, firms go "all or nothing", making no abatement investment in sectors below $\tilde{z}$ as investing in abatement is not profitable for them. On the contrary, above the threshold $\tilde{z}$, firms invest in abatement at their level of output.

2.2 Consumer Preferences

In country i, there are $\bar{L}_i$ homogeneous households. Following Neary (2016), consumer preferences are assumed to be additively separable. Household utility U_i is an integral over the consumption of a continuum of goods $z \in (0, 1)$:

$$U_i[\{x(z)\}] = \int_0^1 u[x(z)]dz \tag{4}$$

. Sectoral sub-utility functions are continuum-quadratic. Due to the free-trade duopoloy with two competing producers in each sector, I follow Neary and Tharakan (2012) and introduce e $\in (0, 1)$ as an inverse measure of product differentiation.

$$u\{x(z)\} = a\left[x_i(z) + x_j(z)\right] - \frac{1}{2}b\left[x_i(z)^2 + x_j(z)^2 + 2e\,x_i(z)\,x_j(z)\right] \tag{5}$$

In the special case of fully identical products, e equals one, while in the reversed case of complete product differentiation, e approaches zero. Note that e can also be interpreted as an indicator for the intensity of competition in each sector. Thus, under duopoly, each household maximizes its utility given the budget constraint $\int_0^1 \left[p_i(z)x_i(z) + p_j(z)x_j(z)\right] dz \leq I_i$. Country i Household income I_i is given by the sum of wage income as well as capital revenue, firm profits and emission

tax revenue, being redistributed to households as a lump-sum transfer:

$$I_i = w_i + r_i\, K_i/\bar{L}_i + \Pi_i/\bar{L}_i + t_i\, E_i/\bar{L}_i. \tag{6}$$

Note that demands in this setting are sensitive to the level of income as consumer preferences are non-quasi-linear. Thus, household utility maximization yields the following inverse demand function for good x_i supplied by the reforming country's firm in sector z:[4]

$$p_i(z) = \frac{a - b\,\left[x_i(z) + e\, x_j(z)\right]}{\frac{1}{2}\left(\lambda_i + \lambda_j\right)} \tag{7}$$

Where λ_i and λ_j are the endogenous household's marginal utilities of income in country i and j.[5] We now impose market clearing in every sector by assuming that the total quantity sold by a country i firm in sector z equals total demand of all households $\bar{L}_i$ and $\bar{L}_j$ for the good of that country i firm:

$$q_i(z) = \bar{L}_i\, x_i + \bar{L}_j\, x_i \tag{8}$$

This transforms (7) to a market demand function for the duopoly case:

$$p_i(z) = \frac{a - \frac{b}{\bar{L}_i + \bar{L}_j}\,\left[q_i(z) + e\, q_j(z)\right]}{\frac{1}{2}\left(\lambda_i + \lambda_j\right)} \tag{9}$$

Being a function of the marginal utilities of income renders demand functions highly non-linear. However, as λ_i and λ_j only depend on economy-wide variables, firms in each sector take marginal utilties of income as given in their decision-making. Thus, following Neary and Tharakan (2012), demands are linear in each firm's sectoral profit maximization, corresponding to the notion that firms are big in their own sector, but small in the economy as an aggregate of sectors.

2.3 Sector Division in Equilibrium

Let me now turn to the equilibrium of across-country duopolist interaction. Featuring the initial symmetric equilibrium prior to the policy reform, this subsection refrains from country indices.

[4] The exogenous demand function parameters a and b are assumed to be identical across countries. This implies $(1/2)\,(a_i + a_j) = a$ as well as $(1/2)\,(b_i + b_j) = b$ Thus, indices are dropped for these.

[5] For the special case of complete symmetry, Neary and Tharakan (2012) derive the marginal utility of income as a function of the income level and the cross-sectoral covariance and distribution of prices. In a symmetric setting, λ can be normalized to one. This does not hold for asymmetry between countries. Here, numerical solutions are obtained for the marginal utility of income.

Closely linked to the sectoral self-selection into abatement, there is a sector-level selection into a mode of competition along the $z \in (0,1)$ continuum:

Table 1: Sectoral self-selection into modes of competition

Competition Mode	**Abatement**	**Price**	**Actual Cost**	**Price-Cost-Margin**
Pure Bertrand $(0 < z < \tilde{z})$	$\xi(z) = 0$	$p^B\left[c^N(z)\right]$	$c^N(z)$	$p^B\left[c^N(z)\right] - c^N(z)$
Quasi-Bertrand $(\tilde{z} < z < z^C)$	$\xi(z) = q(z)$	$p^B\left[c^N(z)\right]$	$c^A(z)$	$p^B\left[c^N(z)\right] - c^A(z)$
Cournot $(z^C < z \leq 1)$	$\xi(z) = q(z)$	$p^C\left[c^A(z)\right]$	$c^A(z)$	$p^C\left[c^A(z)\right] - c^A(z)$

Note: Adapted from Neary and Tharakan (2012).

Recall that at in sectors with z close to 0, there is no investment in abatement, as the marginal costs of abatement investment exceed the marginal benefits of abatement. Essentially skipping stage one, firms in such sectors directly generate output in stage two, switching on the additional, dirty production plant. Thus, firms below the threshold $\tilde{z}$ just engage in a one-shot game, exhibiting Bertrand Behavior. These sectors are labelled "Pure Bertrand" by Neary and Tharakan (2012). As z rises along the continuum, the Pure Bertrand Price (depending on c^N and thus, on $\theta(z)$) increases as well.

Having reached at $\tilde{z}$ implies parity between marginal costs and marginal benefits of abatement. Beyond this threshold, we know that firms invest in abatement corresponding to their output level and thus engage in a two-stage interaction. However, as Maggi (1996) reveals, this does not entail that *all*sectors above $\tilde{z}$ interact in Cournot competition. As shown in stylized Figure 1, at the abatement threshold $\tilde{z}$, the (hypothetical) Bertrand Price set with c^A is located significantly below the Cournot Price set with c^A.[6] Hence, in between, there is an *intermediate* sectoral range from $\tilde{z}$ to z^c in which firms invest in abatement and bear c^A, but actually exhibit Bertrand Behavior and set c^N for their price and quantity choices. This range is denoted as "Quasi-Bertrand"sectors. As marginal cost c^N is a function of z, the Quasi-Bertrand Price continues to go up when moving along the sector interval.

At the threshold $z^c > \tilde{z}$, the Quasi-Bertrand price reaches the Cournot price level. Beyond this threshold, firms interact in Cournot competition, setting prices considering c^A. Note that Cournot prices do not vary along the sectoral interval as c^A (not employing $\theta(z)$) is invariant

[6] Formally, in the case of symmetry, the positive difference between these two price levels hinges on $\hat{a} > c^A$. As simulations show, $p^C(c^A) > p^B(c^A)$ holds except for very small values of $\hat{a}$. Thus, the exogenous parameter a is set as to ensure this condition to hold.

in z. Thus, sectors self-select into three modes of competition. Responses of this selection mechanisms to the environmental policy reform will be analyzed in Section 3.

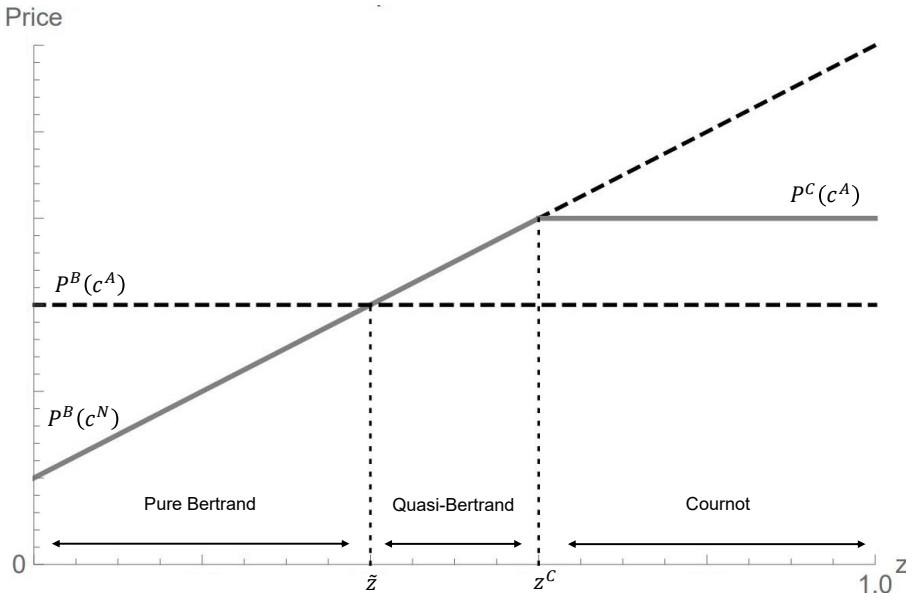


Figure 1: Stylized illustration of sectoral division.

2.4 Prices and Quantities in Equilibrium

Using the inverse market demand functions provided by (9), the price levels p^B and p^C for quasi-Bertrand and Cournot sectors can be derived:

$$p_i^B\left(c_i^N, c_j^N\right) = \frac{(1-e)\left(\hat{a}_i + \hat{a}_j\right)\frac{1}{2} + c_i + e\left(c_j - c_i\right)}{2-e} \quad \text{and} \quad p_i^C\left(c_i^A, c_j^A\right) = \frac{\left(\hat{a}_i + \hat{a}_j\right)\frac{1}{2} + c_i + e\,c_j}{2+e} \tag{10}$$

, where $\hat{a_i} = a_i/\lambda_i$ and $\hat{a_j} = a_j/\lambda_j$. Unlike in the symmetric setting of Neary and Tharakan (2012), expressions in this setting account for possible country asymmetries. Thus, prices of firms do not only depend on their own marginal cost but also on their foreign competitor's cost structure. Due to complete trade freeness, a country i firm charges the same price for its good for domestic sale in i and for exporting to j.

Wee can implicitly determine the Cournot threshold sector z^C by setting Quasi-Bertrand and Cournot prices equal to each other, since both price levels must equal at the threshold z^C:

$$p_i^B\left[c_i^N\left(z^C\right), c_j^N\left(z^C\right)\right] = p_i^C\left[c_i^A,\, c_j^A\right] \tag{11}$$

Note that in case of $c_i = c_j$ pricing equals the expressions in Neary and Tharakan (2012) while in the scenario of identical products ($e = 1$), prices collapse to the standard Bertrand and Cournot expressions.

Quantities in equilibrium can be determined in a similar fashion for Betrand and Cournot sectors[7]. Here, we distinguish between quantities a country i firm sells on its domestic market (subscript ii) and those quantities it exports to country j (subscript ij):

$$q_{ii}^B\left(c_i^N, c_j^N\right) = \frac{\hat{a}_i - c_i + e(c_j - c_i)}{\hat{b}_i(1+e)(2-e)} \quad \text{and} \quad q_{ii}^C\left(c_i^A, c_j^A\right) = \frac{\hat{a}_i - c_i + e(c_j - c_i)}{\hat{b}_i(2+e)}, \tag{12}$$

$$q_{ij}^B\left(c_i^N, c_j^N\right) = \frac{\hat{a}_j - c_i + e(c_j - c_i)}{\hat{b}_j(1+e)(2-e)} \quad \text{and} \quad q_{ij}^C\left(c_i^A, c_j^A\right) = \frac{\hat{a}_j - c_i + e(c_j - c_i)}{\hat{b}_j(2+e)}, \tag{13}$$

where $\hat{a_i} + \hat{a_j} = \hat{a}$ as well as $\hat{b_i} + \hat{b_j} = \hat{b} = (b_i + b_j)/[(L_i + L_j)(1/2)(\lambda_i + \lambda_j)]$. Quantities sold in both modes of competition decrease in the firm's own marginal costs and increase in the marginal costs of its foreign competitor. In addition, it can easily be shown that Bertrand quantities exceed Cournot quantities, corresponding to the feature of Bertrand behaviour as a more "consumer-friendly" mode of competition.

2.5 Factor Market Conditions

To close the model, I make use of standard GOLE labor market conditions. Each household supplies one unit of labor. Supply of labor n country i is exogenously given by $\bar{L_i}$. With full employment, labor demand (on the right side) adjusts to labor supply due to wage flexibility.

$$\bar{L_i} = \int_0^{\tilde{z}} \left[\gamma + \theta(z)\right]\left[q_{ii}^B + q_{ij}^B\right] dz + \int_{\tilde{z}}^{z^C} \gamma \left[q_{ii}^B + q_{ij}^B\right] dz + \int_{z^C}^{1} \gamma \left[q_{ii}^C + q_{ij}^C\right] dz, \tag{14}$$

As indicated by the three summands, labor is demanded across all three modes of competition, as it is required for producing *within* and *beyond* abatement capacity. Within each mode of competition, labor demand is given by the product of total country i firm output in each sector and per-unit labor input requirement.[8]

In a similar fashion, the country-wide capital stock used for abatement investment is supplied by the fixed national capital stock $\bar{K_i}$.[9] Flexibility of capital returns r_i ensures that capital

[7] Generally, in Bertrand competition, cost asymmetries between firms would result into all consumer demand being satisfied by the firm with the lowest marginal costs. In this setting, the product differentiation parameter $e < 1$ ensures a positive output for all firms in case of cost asymmetries induced by the unilateral policy reform.

[8] Appendix (A.1) outlines the closed-form derivation of all factor market conditions.

[9] For simplicity, this setting assumes national capital stocks $\bar{K_i}$ and $\bar{K_j}$ to be fixed within each country, resulting into differentiated capital returns in case of country asymmetry. Assuming international capital mobility would imply that a global capital stock $\bar{K} = K_i + K_j$ could freely move between countries, equalizing rental rates

demand (right side) meets exogenous capital supply:

$$\bar{K}_i = \int_{\tilde{z}}^{z^C} \delta \left[q_{ii}^B + q_{ij}^B \right] dz + \int_{z^C}^{1} \delta \left[q_{ii}^C + q_{ij}^C \right] dz. \tag{15}$$

Due to zero abatement investment below the threshold $\tilde{z}$, capital is just demanded in Quasi-Bertrand and Cournot sectors. Within such sectors, capital demand is given by per unit capital input requirement δ and total output of the country-i-firm.

Finally, emission demand in country i and country j is given by the product of the additional, dirty production plant input requirement θ and total firm output in the respective country in each (non-abating) Pure Bertrand Sector:[10]

$$E_i = \int_0^{\tilde{z}} \left[\theta(z) \right] \left[q_{ii}^B + q_{ij}^B \right] dz \qquad \text{and} \qquad E_j = \int_0^{\tilde{z}} \left[\theta(z) \right] \left[q_{jj}^B + q_{ji}^B \right] dz. \tag{16}$$

Notably, emission demand does not meet an exogenously set level of supply, but adjusts flexibly to changes in factor costs, such as a policy adjustment with respect to country i's emission tax rate t_i.

3 Simulation

3.1 Parametrization and Calibration

As common in the literature on oligopolistic interaction in general equilibrium and country asymmetry, I cannot solve for my endogenous variables analytically (Baccianti and Schenker, 2022). Thus, I solve the model numerically. My model consists of six equations in six unknowns, namely $\tilde{z}$, z^C, w_i, w_j, λ_i and λ_j.[11]. The equations consist of the two labor market conditions ((14), one for each country), two capital market conditions ((15), one for each country) and one pricing condition (11) for each country.

In a purely symmetric setting, the marginal utility of income can be normalized to one for both countries (Neary and Tharakan, 2012). In order to nest the model to this symmetric equilibrium, I set the sum of marginal utilities $\lambda_i + \lambda_j = 2$, ensuring both marginal utilities of income equal one in the special case of symmetry. Furthermore, I define a specific functional

internationally.

[10] Due to parsimonious modelling, emissions are only demanded in sectors that do not abate, as only the additional, dirty production plant requires the input of fossil fuels. While this framework may appear over-simplified, results on leakage would not fundamentally differ in more complex settings.

[11] The rental rate r_i is endogenous as well, but through (3), it can directly be expressed as a function of other endogenous variables and parameters: $r_i = [(w_i + t_i)\theta(\tilde{z})]/\delta$

form for the additional, polluting production plant's input requirement $\theta(z)$. For that, I make use of the polynomial function $\theta_0 + \theta_1 z^{\theta_2}$.

I calibrate my model by assuming values for exogenous parameters, displayed in Table 2. Prior to the unilateral policy reform, I assume complete symmetry with respect to the choice of parameters across countries. Apart from carbon tax rates, the choice of most parameter values is based on Neary and Tharakan (2012).[12] Prior to the reform, I set carbon taxes in both countries to 10. In line with empirical evidence on energy-intensive sectors, this will ensure that roughly around 20 to 30% of firm factor costs are spent on emission-intensive fuels across sectors in my symmetric equilibrium.

Parameter	**Description**	**Value**
a_i, a_j	demand intercept	100
b_i, b_j	demand slope	10
$\bar{L}_i$, $\bar{L}_j$	no. of households	100
e	degree of product differentiation	0.7
t_i, t_j	emission tax	10
$\bar{K}_i$, $\bar{K}_j$	country-specific capital stock	70
δ	capital input requirement	1.3
γ	production input requirement	1.3
θ_0	additional plant input function intercept	1.3
θ_1	additional plant input function slope	1
θ_2	additional plant input function exponent	2

Table 2: Calibration of Model Parameter Values

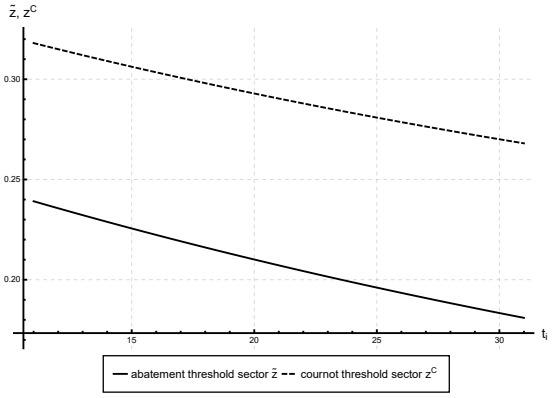
3.2 Simulation Results

I then implement the unilateral environmental policy reform, tripling country i's carbon tax rate from 10 to 30.[13] Doing so, I roughly approximate the relative cost increase from pre-existing *implicit* carbon taxes (around USD 40 per ton of CO2 in energy-intensive sectors) to additionally introduced explicit carbon taxing (price EU ETS allowance of around USD 100 per ton of CO2 in 2023). The unilateral carbon tax rate removes the symmetry between the countries, resulting into differing endogenous variables in each country.

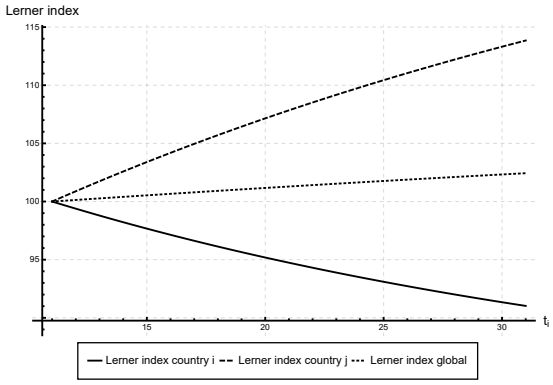
3.2.1 Effects on Sector Thresholds and Competitiveness

First of all, adjustments to the sectoral thresholds of competition modes outlined in section 2.3 are to be highlighted as an important implication of the unilateral policy reform. As fig-

[12] In Appendix (A.3), a detailed sensitivity analysis accounts for the impact of variations in parameter values.
[13] A Mathematica workbook containing the system of equations and simulation is available upon request.



(a) Change in Sector Thresholds



(b) % Change in Lerner Index of Market Power

Figure 2: Change in sector thresholds and cost-pass-through rates

ure 2a shows, the unilateral policy reform induces both sector thresholds $\tilde{z}$ and z^C to fall monotonously.[14] The intuition goes as follows: In Country i, the rise in the emission tax increases the marginal benefit of abatement investment, shown on the right side of (3). Thus, abatement investment becomes attractive for more sectors, lowering the abatement investment threshold $\tilde{z}$. Through $\theta(\tilde{z})$ as part of the trade-off condition, the policy reform spills over to country j as well.

In response to the policy reform, more sectors interact in Cournot competition and invest in emission abatement. As it it well known, Cournot competition is characterized by higher degrees of market power, mark-ups and cost-pass-troughs.[15]

The policy reform's effect on the global economy's market structure is quantified using a refined formulation of the *Lerner Index of Market Power*, which captures the degree of imperfect competition through the relative markup of prices over marginal costs. The index is defined as a continuous integral over the continuum of sectors:

Figure (2b) shows the resulting decomposition across the three segments of competition modes:

$$L = \int_0^{\tilde{z}} \frac{p^B(z) - c^N(z)}{p^B(z)}\, dz + \int_{\tilde{z}}^{z^C} \frac{p^B(z) - c^A(z)}{p^B(z)}\, dz + \int_{z^C}^{1} \frac{p^C(z) - c^A(z)}{p^C(z)}\, dz \tag{17}$$

Country i firms are directly affected by the policy reform. Facing competition from country j firms not subjected to the hike in emission taxes, country i firms are only able to pass on

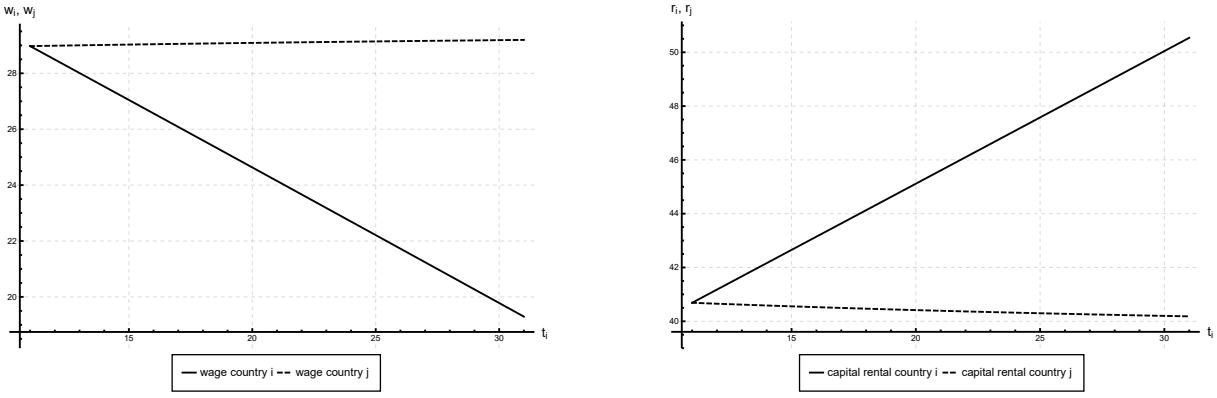
[14] Neary and Tharakan (2012) show that threshold z^C strictly moves in the same direction as $\tilde{z}$. Thus, this analysis just focuses on the latter.

[15] For the case of symmetry, Neary and Tharakan (2012) show that the Lerner Index of Cournot Sectors strictly exceeds that of Pure Bertrand and Quasi-Bertrand Sectors.

small shares of the production cost increase to consumers via output prices. Thus, their profits and margins decline, reducing the Lerner Index among them (solid line). On the contrary, the Lerner Index of country j firms (dashed line) increases, as they gain comparative advantage and increase cost pass-troughs. Notably, these two effects do not balance out completely, being depicted in the rise of the Lerner index average across all firms (dashed line). A driving force behind the sign of the overall effect can be attributed to the extensive margin, i.e. the increase in Cournot sectors across both countries. Hence, the unilateral environmental policy reform enhances oligopolization and market power across the international economy.

3.2.2 Effect on Factor Prices

Having outlined the effects on sectoral thresholds, this analysis now turn to endogenous wage and rental rates. As shown in Figure 3a, the wage rate in the reforming country i (solid line) decreases significantly while wages increase slightly in the non-reforming country j (dashed line):



(a) Change in wages in country i and j

(b) Change in rental rates in country i and j

Figure 3: Change in endogenous factor prices

Again, the intuition employs the abatement trade-off condition shown in (3): The increase in marginal benefit of abatement investment in the reforming country reduces demand for labor in country i, as labor is used more intensively in absence of abatement investment.[16] In country j, the effect is contrary as the marginal benefit of abatement investment declines with $\theta(\tilde{z})$ falling and the carbon tax t_j staying constant. Thus, labor demand decreases in the non-reforming country. However, this spillover effect on country j's wage rate shows to be small. Hence, in contrast to frameworks of constant mark-ups, across-country wage spillover effects do not appear to be strongly relevant in my setting.

[16] Recall that per-unit labor input requirement is $\gamma + \theta(z)$ in absence of abatement investment and γ with abatement investment at output level.

The capital rental rate is depicted on the left side of the trade-off condition shown in (3). Intuitively, as shown in 3, the effect across countries is just the opposite: Whereas capital rental strongly rises in the reforming country, it slightly declines in country j.

3.2.3 Effect on Emissions

As emission leakage to unregulated countries is a significant concern in the context of unilateral environmental reforms, the policy's effect on emissions in the two countries constitutes a major part of analysis.

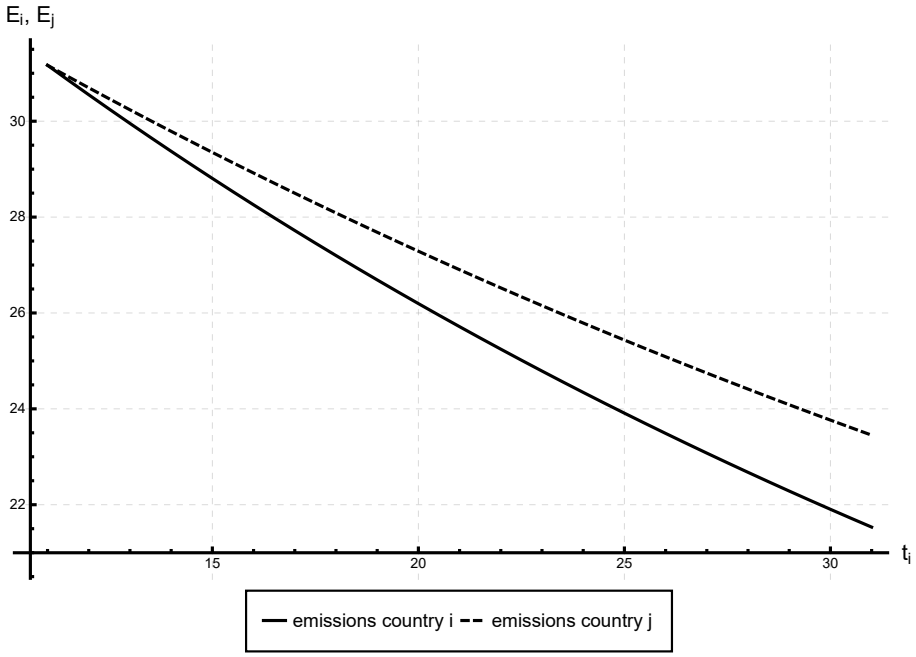


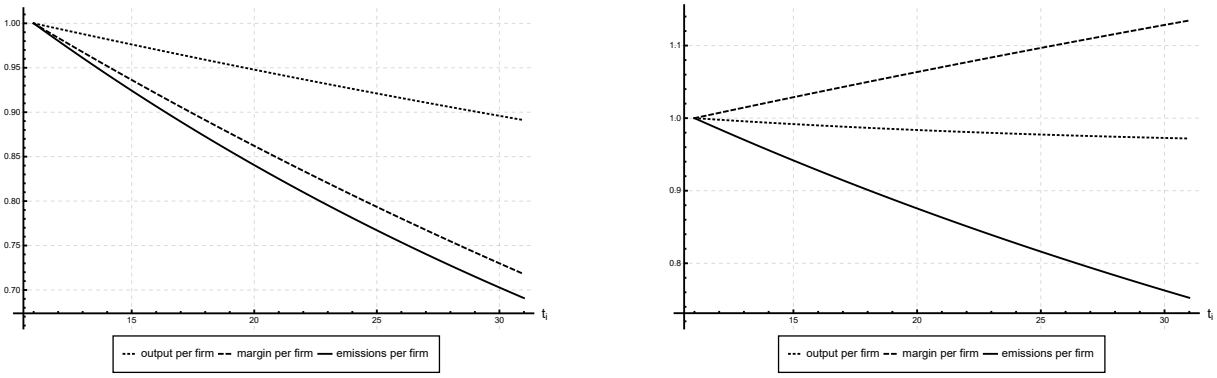
Figure 4: Change in emisions in country i and country j

In response to the unilateral reform, Figure (4) shows a strong decrease in national emission levels. Intuitively, in the reforming country i, emissions decline by around 30% (solid line). Notably, emissions in the non-reforming country j (dashed line), falling by around 25%, decrease almost as strongly as in the reforming country. This results into a negative leakage rate as high as around 80%, greatly exceeding estimations by Baccianti and Schenker (2022).

To further look at the mechanisms at work, let us recall how national emissions are defined: In each country, emission demand is given by the product of production input requirement in absence of abatement investment $\gamma + \theta(z)$, aggregated over all sectors below the abatement threshold sector $\tilde{z}$. Thus, the integral denotes the extensive margin, while per-unit input requirement and firm output accrue to the intensive margin.

First of all, let us illustrate the effect of changes to firm-level output volumes. Figure (5)

shows the change in output levels (dashed line) and price-cost-margins (dotted line) in a Pure Bertrand (i.e. polluting) sector firm in country i and country j. Each value is normalized to one at the benchmark scenario of equal carbon taxes.



(a) Output level and cost margin in country i

(b) Output level and cost margin in country j

Figure 5: Change in output levels and price-cost margin across countries

Output per firm in country i decreases by around 10%. In relative terms, this is significantly less as compared to the decline in the country's emissions (solid line). This indicates that as a key feature of this model setup, effects at the extensive margin also play a substantial role in the overall environmental effects. Furthermore, in line with findings presented in section 3.2.1, price-cost margins for firms in country i decrease, as the production cost rise evoked by the policy reform cannot be fully passed on to consumer prices.

In the non-reforming country j, firms gain a comparative cost advantage due to the policy reform in country i. As a profit-maximizing response in a setting with variable markups, they react by increasing price-cost margins instead of output levels. Thus, output levels fall slightly also among firms in the non-reforming country. This is the key mechanism driving down the non-reforming country's emissions in Baccianti and Schenker (2022). This framework adds to this intensive-margin channel by enclosing an additional effect at the extensive-margin.

The relative magnitude of both channels is identified in a numerical decomposition.[17] Following Forslid et al. (2018), I decompose national emissions of country i and j into within-firm and across-firm effects:

[17] Further details are provided in Appendix (A.2).

$$\frac{dE_i}{dt_i} = \int_0^{\tilde{z}} \frac{d\theta(z)}{dt_i} \left[q_i^B\right] dz + \int_0^{\tilde{z}} \theta(z) \frac{d\bar{q_i^B}}{dt_i} dz + \frac{d\tilde{z}}{dt_i} \theta(\tilde{z})\, q_i^B(\tilde{z}) \qquad \frac{dE_j}{dt_i} = \int_0^{\tilde{z}} \frac{d\theta(z)}{dt_i} \left[q_j^B\right] dz + \int_0^{\tilde{z}} \theta(z) \frac{d\bar{q_j^B}}{dt_i} dz + \frac{d\tilde{z}}{dt_i} \theta(\tilde{z})\, q_j^B(\tilde{z}). \tag{18}$$

The first line contains an *input effect* , capturing the change in per-unit sector-level "penalty" input requirement $\theta(z)$. As $\theta(z)$ does not vary in t_i, the effect of the first line is zero.[18] The second line captures the *output effect* (OUT) referring to the change in average Pure Bertrand firm-level output, keeping the integral of $\theta(z)$ constant at the benchmark scenario of $t_i = 10$. The third line depicts the *extensive margin effect* (EXT), denoting the change in the integrals upper bound $\tilde{z}$, multiplied by firm-level emissions at the thresold sector $\tilde{z}$ at $t_i = 10$. This decomposition is executed numerically. Note that as shown by Najjar and Cherniwchan (2021), additionally there is an interaction effect (INT) accounting for across-channel interactions that constitutes a residuum term.

As outlined by the decomposition result, just around one third of the total emission reduction in the reforming country i is achieved through an intensive margin output effect within firms. However, two thirds of the effect attribute to the extensive margin, accounting for increases in the share of sectors that invest in emission abatement (and thus do not pollute). In the non-reforming country, just around 12% of the total emission reduction are attained through the firm-level output effect and almost 88% accrue to the extensive margin. Notably, the extensive margin is of equal size for both countries. In total, the non-reforming country attains around 80% of emission reduction achieved in the reforming country.

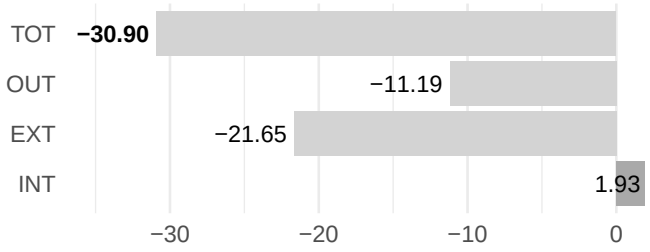


Figure 6: Decomposition of %-change in country i Emissions

[18] However, $\theta(z)$ matters for determining the interaction effect as residuum term.

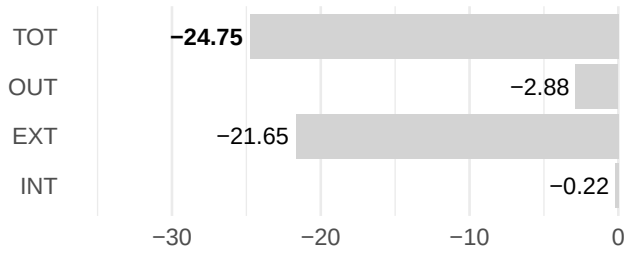


Figure 7: Decomposition of %-change in country j Emissions

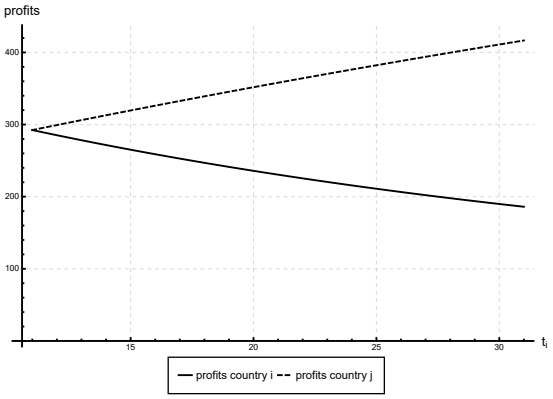
3.2.4 Effect on Welfare

In order to derive an approximation for welfare across both countries, we need to solve for national income, as it determines consumption possibilities of households.[19]

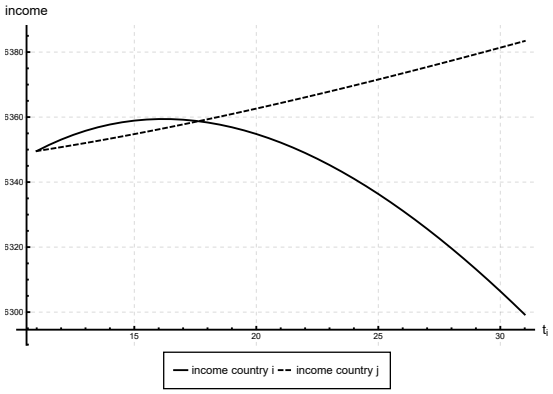
To obtain an expression for income as expressed in equation (6), we can build on the numerical solutions for labor wages, capital rental and emissions. Aggregate firm profits for both countries (Π_i, Π_j) need to be computed by integrating over the product of price-cost margins and quantities, summing over all sector types. For aggregate profits in country i, this gives:

$$\begin{aligned}\Pi_i \;=\; & \int_0^{\tilde{z}} \left(p_i^B(z) - c_i^N(z)\right) q_i^B(z)\, dz + \int_{\tilde{z}}^{z^C} \left(p_i^B(z) - c_i^A(z)\right) q_i^B(z)\, dz \\ & + \int_{z^C}^{1} \left(p_i^C(z) - c_i^A(z)\right) q_i^C(z)\, dz. \end{aligned} \tag{19}$$

We obtain a numerical solution for aggregate profits by using the closed-form expressions for prices and quantities. Inserting this expression into equation (6) yields aggregate income for each country.



(a) Aggregate profits across both countries



(b) Aggregate income across both countries

[19] An alternative approach would be to derive welfare directly from the utility function, which integrates over all sectoral sub-utility functions. While conceptually more straightforward, this method is computationally more demanding and would not yield results qualitatively different from the income-over-price-index measure used here.

Due to the comparative advantage induced by country i's unilateral reform, country j's income rises monotonously. Due to the mechanical rise in emissions tax income counter-acted by the policy-induced cost shock, country i's income exhibits a Laffer-curve pattern. Hence, the effect on the reforming country's nominal income level hinges on the magnitude of the policy reform.

In addition to nominal income available to households, measuring overall welfare needs to account for changes in consumer prices evoked by the emissions tax rise. Hence, we define country-wide price indices by integrating over all sectoral prices for each country, weighted by output quantities. The aggregate price index for output by country i firms is thus defined as:

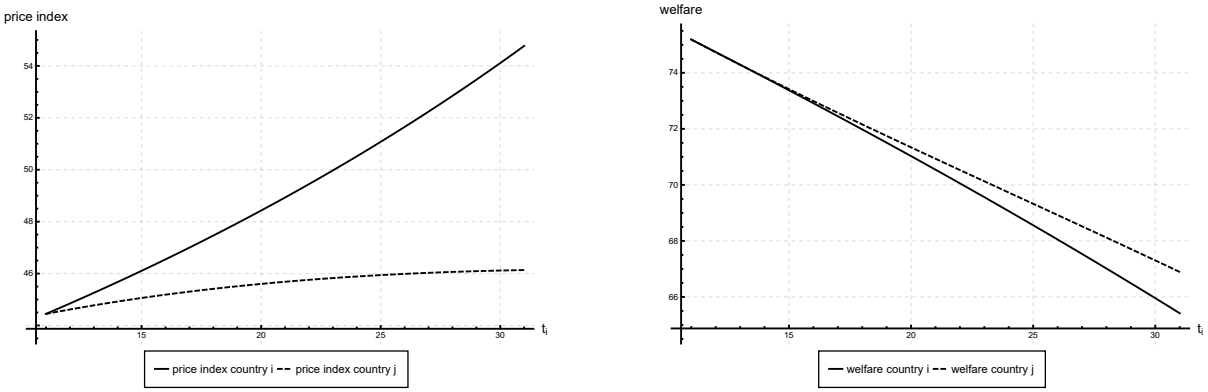
$$\bar{p}_i(t) = \frac{\int_0^{\tilde{z}} p_i^B(z,t)\, q_i^B(z,t)\, dz + \int_{\tilde{z}}^{z^C} p_i^B(z,t)\, q_i^B(z,t)\, dz + \int_{z^C}^1 p_i^C(z,t)\, q_i^C(z,t)\, dz}{\int_0^{\tilde{z}} q_i^B(z,t)\, dz + \int_{\tilde{z}}^{z^C} q_i^B(z,t)\, dz + \int_{z^C}^1 q_i^C(z,t)\, dz}. \tag{20}$$

In the case of perfectly integrated markets, both $\bar{p}_i(t)$ and $\bar{p}_j(t)$ enter symmetrically into each country's welfare expression. To account for trade frictions, we reduce the weight assigned to the trading partner's price index by 10%. This gives the following welfare approximation for country i:

$$W_i(t) \;\approx\; \frac{I_i(t)}{\bar{p}_i(t) \;+\; \tau\, \bar{p}_j(t)} \quad \text{with } \tau, \tag{21}$$

where τ accounts for trade frictions.[20]

Figure (9a) outlines that prices in both countries' production rise, though the increase in country j (solely based on general equilibrium adjustments) shows to be significantly weaker. This underlines the importance of considering price indices for estimating welfare.



(a) Price index across both countries

(b) Welfare across both countries

[20] We recognize the social costs associated with CO_2 emissions. For analytical clarity, however, the welfare measure employed here abstracts from environmental disutility.

igure (9b) shows that welfare in country i declines by 13% in response to the unilateral reform. The welfare loss in its non-reforming trading partner is slightly smaller at 11%. Thus, while the unilateral reform is environmentally effective, it entails notable costs in terms of greater oligopolization, reflected in higher markups and reduced competitiveness, as well as a welfare reductions across both countries.

4 Conclusion

This paper develops a GOLE model in the spirit of Neary and Tharakan (2012) to examine the consequences of a unilateral environmental policy reform for emission leakage, explicitly incorporating trade dynamics, oligopolistic competition, and capital-intensive abatement. The framework builds on the strategic mechanism of Kreps and Scheinkman (1983): in a first stage, firms choose abatement investments, which shape their cost structures, emission intensities, and ultimately their mode of competition (Bertrand versus Cournot) in the subsequent stage.

The unilateral reform increases the share of sectors that adopt abatement technologies, thereby driving down emissions not only in the reforming country but also in its trading partner. Calibrated simulations yield a *negative* leakage rate of roughly 80%, pointing to substantial cross-border emission reductions. Qualitatively, this result contrasts sharply with the predictions of standard CGE models, while quantitatively it exceeds the magnitude of negative leakage typically identified in oligopolistic settings. A decomposition shows that the strongest effects occur at the extensive margin, as more sectors adopt abatement, which represents a distinct feature of this framework. At the same time, emissions also decline at the intensive margin, as firms in both countries cut output in response to the policy.

The reform further shifts the composition of competition across the global economy: a share of sectors moves from Bertrand to Cournot competition, reducing overall competitiveness. Welfare correspondingly declines in both countries. Taken together, the unilateral reform underscores a fundamental *policy dilemma*: while it achieves substantial and even amplified reductions in global emissions, it does so at the cost of increased oligopolization, weaker competitiveness, and lower consumer welfare.

A Appendix

A.1 Derivation of Factor Market Conditions in closed form

First, quantities are derived in closed form. Adding up outputs for domestic (12) and export sale (13) yields the total output quantity of a country i firm:

$$q^B\left(c_i^N, c_j^N\right) = \frac{\left(\hat{b_i} + \hat{b_j}\right)\left[-c_i + e(c_j - c_i)\right] + \hat{a_i}\hat{b_j} + \hat{a_j}\hat{b_i}}{\hat{b_i}\hat{b_j}(1+e)(2-e)}, \tag{A.1}$$

$$q^C\left(c_i^A, c_j^A\right) = \frac{\left(\hat{b_i} + \hat{b_j}\right)\left[-c_i + e(c_j - c_i)\right] + \hat{a_i}\hat{b_j} + \hat{a_j}\hat{b_i}}{\hat{b_i}\hat{b_j}(2+e)}. \tag{A.2}$$

Note that both expression collapse to those derived in Neary and Tharakan (2012) in case of symmetry, i.e. $c_i = c_j$, $\hat{a_i} = \hat{a_j}$ and $\hat{b_i} = \hat{b_j}$.

Integrating over the product of quantities and respective input requirement for all three sector types yields a closed-form solution for the factor market conditions displayed in equations (14) and (15). Note that penalty input requirement θ is defined as a function of z, i.e. $\theta_0 + \theta_1\, z^{\theta_2}$, while within-abatement production input γ as well as capital input requirement δ are treated as constants.

A.2 Decomposition of Total Emissions

Recall that emissions in country i are defined as:

$$E_i = \int_0^{\tilde{z}} \theta(z)\, \left[q_i^B\right] dz, \tag{A.3}$$

for which we can use the following shorthand notation:

$$E^i = EXT \cdot \theta(z) \cdot OUT. \tag{A.4}$$

To analyze the change in global emissions, we apply the product rule:

$$\triangle E^W = \triangle(EXT \cdot \theta(z) \cdot OUT). \tag{A.5}$$

Since $\theta(z)$ is constant in t_i, it factors out:

$$\triangle E^W = \theta(z) \cdot (\triangle EXT \cdot OUT + EXT \cdot \triangle OUT + \triangle EXT \cdot \triangle OUT)\,. \tag{A.6}$$

The decomposition consists of three key effects:

- $\theta(z) \cdot \triangle EXT \cdot OUT$: Change at the extensive margin, holding output of emitters (Pure Bertrand Firms) constant.
- $\theta(z) \cdot EXT \cdot \triangle OUT$: Change in output among incumbent emitters (Pure Bertrand Firms), holding the extensive margin constant
- $\theta(z) \cdot \triangle EXT \cdot \triangle INT$: An interaction effect capturing simultaneous changes in both components.

The interaction term is given by:

$$\mathcal{INT} = \theta(z) \cdot \triangle EXT \cdot \triangle OUT, \tag{A.7}$$

where $\theta(z)$ remains as a scaling factor.

A.3 Sensitivity Analysis

To complement the analysis in the main text and to test the robustness of the main results, this sensitivity analysis varies, i.e. the product differentiation parameter e, the capital input coefficient of country i, δ_i, the capital stock of country i, K_i as well as the slope (θ_1) and exponent (θ_2) defining the additional input required for production above abatement scope.

Table 3: Variation of product differentiation parameter e

Outcome	$e = 0.7$		$e = 0.5$		$e = 0.9$	
	Baseline	%-change	Baseline	%-change	Baseline	%-change
Threshold sector $\tilde{z}$	0.24	-24.32	0.25	-21.94	0.22	-27.23
Threshold sector z^C	0.32	-15.72	0.30	-17.46	0.35	-13.76
Emissions country i	31.17	-30.91	31.87	-28.74	30.91	-33.41
Emissions country j	31.17	-24.76	31.87	-23.35	30.91	-26.83
Lerner index global	0.03	2.82	0.04	-0.72	0.02	11.56
Lerner index country i	0.03	-19.69	0.04	-17.34	0.02	-21.32
Lerner index country j	0.03	25.33	0.04	15.91	0.02	44.45
Welfare country i	75.19	-12.99	62.65	-10.13	95.06	-17.12
Welfare country j	75.19	-11.03	62.65	-9.81	95.06	-13.97

Notes: Baseline values represent equilibrium outcomes prior to the unilateral reform ($t_i = 10$). *%-change* values provide the relative change in response to the reform ($t_i' = 30$). The product differentiation parameter e ranges from 0.5 (high differentiation) to 0.9 (low differentiation), with $e = 0.7$ (default scenario in the main text) serving as the intermediate case.

Table 4: Variation of capital input coefficient δ_i

Outcome	$\delta_i = 1.3$		$\delta_i = 1.0$		$\delta_i = 1.7$	
	Baseline	%-change	Baseline	%-change	Baseline	%-change
Threshold sector $\tilde{z}$	0.24	-24.32	0.08	-32.60	0.34	-21.13
Threshold sector z^C	0.32	-15.72	0.23	-9.07	0.39	-16.53
Emissions country i	31.17	-30.91	9.93	-34.73	46.79	-29.35
Emissions country j	31.17	-24.76	9.93	-32.56	46.79	-21.59
Lerner index global	0.03	2.82	0.03	2.51	0.03	3.62
Lerner index country i	0.03	-19.69	0.03	-4.38	0.03	-31.29
Lerner index country j	0.03	25.33	0.03	9.39	0.03	38.53
Welfare country i	75.19	-12.99	85.87	-12.42	77.53	-16.37
Welfare country j	75.19	-11.03	75.69	-9.04	86.75	-15.53

Notes: Baseline values represent equilibrium outcomes prior to the unilateral reform ($t_i = 10$). *%-change* values provide the relative change in response to the reform ($t_i' = 30$). Country i's capital input coefficient δ_i ranges from 1.0 (high capital productivity) to 1.7 (low capital productivity), with $\delta_i = 1.3$ (default scenario in the main text) serving as the intermediate case. Country j's capital input coefficient is held constant at $\delta_j = 1.3$.

Table 5: Variation of capital stock K_i

Outcome	$K_i = 70$		$K_i = 90$		$K_i = 50$	
	Baseline	%-change	Baseline	%-change	Baseline	%-change
Threshold sector $\tilde{z}$	0.24	-24.32	0.09	-32.11	0.36	-20.70
Threshold sector z^C	0.32	-15.72	0.23	-9.59	0.41	-16.57
Emissions country i	31.17	-30.91	11.00	-34.51	50.10	-29.14
Emissions country j	31.17	-24.76	11.00	-32.09	50.10	-21.12
Lerner index global	0.03	2.82	0.03	2.41	0.03	3.66
Lerner index country i	0.03	-19.69	0.03	-5.24	0.03	-33.84
Lerner index country j	0.03	25.33	0.03	10.05	0.03	41.17
Welfare country i	75.19	-12.99	84.69	-12.16	78.91	-17.29
Welfare country j	75.19	-11.03	75.07	-8.85	90.62	-16.71

Notes: Baseline values represent equilibrium outcomes prior to the unilateral reform ($t_i = 10$). *%-change* values provide the relative change in response to the reform ($t_i' = 30$). Country i's capital stock K_i ranges from 50 (low) to 90 (high), with $K_i = 70$ (default scenario in the main text) serving as the intermediate case. Country j's capital stock is held constant at $K_j = 70$.

Table 6: Variation of input coefficient θ_1 (function slope)

Outcome	$\theta_1 = 1.0$		$\theta_1 = 0.7$		$\theta_1 = 1.3$	
	Baseline	%-change	Baseline	%-change	Baseline	%-change
Threshold sector $\tilde{z}$	0.24	-24.32	0.25	-25.01	0.23	-23.78
Threshold sector z^C	0.32	-15.72	0.35	-14.91	0.29	-16.21
Emissions country i	31.17	-30.91	31.82	-31.70	30.65	-30.27
Emissions country j	31.17	-24.76	31.82	-24.70	30.65	-24.88
Lerner index global	0.03	2.82	0.03	2.65	0.03	2.94
Lerner index country i	0.03	-19.69	0.03	-20.38	0.03	-19.26
Lerner index country j	0.03	25.33	0.03	25.68	0.03	25.14
Welfare country i	75.19	-12.99	85.50	-14.62	69.48	-12.02
Welfare country j	75.19	-11.03	85.50	-12.14	69.48	-10.40

Notes: Baseline values represent equilibrium outcomes prior to the unilateral reform ($t_i = 10$). *%-change* values provide the relative change in response to the reform ($t_i' = 30$). Recall that the additional input required for production above abatement scope is defined by the function $\theta = \theta_0 + \theta_1 z^{\theta_2}$. Here, its slope parameter is varied from $\theta_1 = 0.7$ (low) to $\theta_1 = 1.3$ (high) with $\theta_1 = 1.0$ (default scenario in the main text) serving as the intermediate case.

Table 7: Variation of input coefficient θ_2 (function exponent)

Outcome	$\theta_2 = 2.0$		$\theta_2 = 1.5$		$\theta_2 = 2.5$	
	Baseline	%-change	Baseline	%-change	Baseline	%-change
Threshold sector $\tilde{z}$	0.24	-24.32	0.22	-24.69	0.26	-24.56
Threshold sector z^C	0.32	-15.72	0.27	-19.13	0.36	-12.55
Emissions country i	31.17	-30.91	29.90	-29.79	32.17	-31.88
Emissions country j	31.17	-24.76	29.90	-26.38	32.17	-24.02
Lerner index global	0.03	2.82	0.03	4.09	0.03	1.48
Lerner index country i	0.03	-19.69	0.03	-17.79	0.03	-21.52
Lerner index country j	0.03	25.33	0.03	25.97	0.03	24.48
Welfare country i	75.19	-12.99	66.54	-13.74	85.70	-11.85
Welfare country j	75.19	-11.03	66.54	-12.43	85.70	-9.15

Notes: Baseline values represent equilibrium outcomes prior to the unilateral reform ($t_i = 10$). *%-change* values provide the relative change in response to the reform ($t_i' = 30$). Recall that the additional input required for production above abatement scope is defined by the function $\theta = \theta_0 + \theta_1 \, z^{\theta_2}$. Here, its exponent is varied from $\theta_2 = 1.5$ (low) to $\theta_2 = 2.5$ (high) with $\theta_2 = 2.0$ (default scenario in the main text) serving as the intermediate case.

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