Optimal Climate Policy in the Presence of Another Country's Climate Policy

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Abstract:

The allowances in an emission trading system (ETS) are commonly allocated for free to the emission-intensive and trade-exposed sector, e.g., in the form of output-based allocation (OBA). Recently an approach combining OBA with a consumption tax has been proposed to mitigate carbon leakage. This paper evaluates the potential outcome in a game of climate policies, by examining the Nash equilibrium outcome of a non-cooperative policy instrument game between regions who regulate their emissions separately. We construct a computable general equilibrium model and investigate the case when regions can choose to supplement their ETS with OBA and/or with a consumption tax, in the presence of another regulating region. In the context of the EU and China, we show how regional interests combined with a national climate target, may lead to different climate policy combinations.

1. Introduction

In the aftermath of the 2015 Paris climate agreement, most countries' nationally determined contributions (NDCs) includes a plan for establishing a market-based mechanism, or carbon trading system, in order to tackle climate change (Andresen et al., 2016). The policymakers in these countries, however, are well aware that unilateral action leads to carbon leakage, such as relocation of emission-intensive and trade-exposed industries (EITE) (Taylor, 2005).

As a result, policymakers have either excluded the EITE sector from regulation or found other anti-leakage solutions. In the EU emission trading system (ETS), for instance, the EITE industries exposed to carbon leakage are given a large number of free allowances.[1] Similarly, the allowances for the EITE sector in China's ETS will also be allocated for free (Xiong et al., 2017). The allocation is typically based on benchmarks such as production output (Neuhoff et al., 2016b), often referred to as output-based allocation (OBA) (Böhringer & Lange, 2005). While most studies find that OBA would mitigate carbon leakage, it ends up however stimulating too much production and consumption of the EITE goods. The reason is that OBA works as an implicit production subsidy, and consequently the incentives to substitute to less carbon-intensive products are weakened. Furthermore, with uncertainty about leakage exposure for the sectors, policymakers may also overcompensate the sector with free allowances (see e.g., Sato et al., 2015, and Martin et al., 2014).

Most studies have shown that carbon leakage mitigation with Border Carbon Adjustments (BCAs), with charges on embedded carbon imports and refunds on export of EITE goods, would outperform OBA (Böhringer et al., 2012; Fischer & Fox, 2012; Monjon & Quirion, 2011). BCAs may however be politically contentious (Böhringer et al., 2017), and experts seem not agree on whether it is compatible with current WTO rules[2] (Horn & Mavroidis, 2011; Ismer & Haussner, 2016; Tamiotti, 2011). Recently, another approach has been proposed. Particularly, Böhringer et al. (2017) shows that it is welfare improving for a country, which has already implemented a carbon tax along with output-based rebating (OBR) to EITE goods, to introduce a consumption tax on top of the same EITE goods. Kaushal and Rosendahl (2020) shows that it is welfare improving under specific circumstances for a single region to introduce a consumption tax on EITE goods, when the OBA is already implemented jointly in two regulating regions for the same EITE goods. Moreover, both Böhringer et al. (2017), and Kaushal and Rosendahl (2020) finds that the consumption tax has an unambiguously global welfare improving effect. A consumption tax may not face the same WTO rule challenges as a BCA

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[1] In phase 3 (2013-2020) the commission estimates that 43% of the total allowances will be handed out to industrial installations exposed to a significant risk of carbon leakage (EU, 2017)

[2] One reviewer suggested that another fundamental obstacle is the absences of data about the embodied carbon of manufacturing process in foreign countries. Hence, using domestic level may be very incorrect and trigger legal issues.

(Munnings et al., 2019; Neuhoff et al., 2016a), and the administrative cost of the consumption tax will likely be limited if set equal to the OBA "benchmarks" (Ismer & Haussner, 2016; Neuhoff et al., 2016b).

Neither Böhringer et al. (2017) or Kaushal and Rosendahl (2020) examines how anti-leakage measure in other locations may affect the level of OBA and/or consumption tax at home, or whether OBA and/or consumption tax can be used strategically in the presence of other regulating regions. Such a strategy becomes particularly policy-relevant since there are several countries pursing their local ETSs, with different emission reduction targets. This poses a policy problem that is different from e.g., the one EU faced when it initiated its ETS in 2005. In this paper, we build on the analysis in Böhringer et al. (2017) and Kaushal and Rosendahl (2020), and investigate the optimal choice of OBA and/or consumption tax in the presence of another region's OBA and/or consumption tax. Mainly, we are interested in the non-cooperative game of policy instruments between the EU ETS and the Chinese ETS, as both markets will have a variant of OBA for the EITE goods in their upcoming phases.

We construct a stylized numerical computable general equilibrium (CGE) model based on Kaushal and Rosendahl (2020). The CGE model provides a basis for describing the characteristics of the regions, which are players in our non-cooperative game of policy instruments. The two region's emission target is set, and the players choose simultaneously their level of anti-leakage measure OBA and/or consumption tax. The choice of level in each region is the Nash Equilibrium (NE) outcome, in which the decision is the best response to the actions of the other region. While our numerical model is based on Kaushal and Rosendahl (2020), there are some important differences. First, we examine the case for three different regions, where two of the regions have an emission trading system. Second, while Kaushal and Rosendahl consider OBA and some shares of consumption tax based on OBA, this paper considers policy combinations with different allocation factors for both OBA and consumption tax. Finally, this paper focuses on the non-cooperative policy instrument game of optimal climate policy for two regulating regions with separate emission trading systems, whereas Kaushal and Rosendahl look at two regions that are involved in a joint emission trading system and only one of them considers imposing a consumption tax.

The paper relates to different strands of literature. First, there are number of studies analyzing carbon leakage. The seminal paper by Markusen (1975) derives the first-best combination of an emission tax and a tariff on imported goods, where the latter depends on both leakage and terms-of-trade effects. Hoel (1996) shows the optimal combination of an emission tax and a carbon tariff, including the indirect emission effects of the tariff as well (see also Copeland, 1996). Most numerical studies quantifying carbon leakage using multi-region multi-sector CGE models of the world economy, suggest a leakage in the range of 5-30% (Böhringer et al., 2012; Zhang, 2012) with a somewhat higher rate for the EITE industries (Fischer & Fox, 2012; Ponssard & Walker, 2008).

The leakage mainly occurs through three channels. The first channel is the fossil fuel market, where reduced fuel demand in the emission regulating regions reduces the international fuel prices. This in turn stimulates the fuel consumption and hence emissions in the unregulating regions. The second channel is the competitiveness channel for the emission-intensive and trade-exposed goods (e.g. steel, cement or chemical products). The affected industries in the regulating regions claim that the emission restrictions raise their production costs, resulting in a competitive disadvantage on the world market. As a result, the regulating regions achieve lower emissions level locally but risks losing jobs and industry to the unregulated regions, as well as higher foreign emissions (Felder & Rutherford, 1993). The third channel is through outsourcing production or moving to other regions (Markusen et al., 1993; Markusen et al., 1995; Martin et al., 2014). The policy debate frequently focuses on leakage through the second and third case, reflecting the concern of regulated EITE industries adverse production impacts and the risk of firms reallocating.

Our paper also relates to the substantial literature on strategic policy and trade. The seminal paper by Brander and Spencer (1985) finds that when firms compete in quantities (Stackelberg competition), the optimal policy tends to be a subsidy to the home firm. The seminal paper by Eaton and Grossman (1986) finds that the optimal policy tends to be a tax if the firms are price-setters (Betrand situation). In terms of environmental policy, the question has been to what extent a government should consider polices that best serves a nation's export industry (Copeland & Taylor, 2004; Greaker, 2003). Barrett (1994) finds support for the outcomes by both Brander and Spencer (1985), and Eaton and Grossman (1986), but argues that the policy implications are sensitive to assumptions about entry and market structure (Barrett, 1994; Copeland & Taylor, 2004). Our work departs from the existing literature on strategic climate policy and trade in, first, its use of a stylized multi-sector multi-region CGE model where markets are assumed to be competitive. The importance of general equilibrium responses to global warming abatement policies are established by a number of studies (Carbone et al., 2009). We use the quantitative content of the general equilibrium model to inform the game-theoretic analysis. This allows us to examine complex issues such as heterogenous countries and general equilibrium effects, which are difficult to analyze in a purely analytical model. [3] Second, this paper considers a broader range of policy combinations - such as output-based allocation and/or consumption tax - with a fixed emission target in the regulating regions. The motivation for this is the current situation

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[3] Jakob et al. (2014) review the literature on consumption vs. production-based instruments and conclude that to assess the full effects of the policies, it is necessary to assess the global general equilibrium effects.

in Europe and China, where the countries' NDCs include an emission target. At the same time, there is significant concern for the domestic EITE producer and carbon leakage. As both regions consider anti-leakage measure to their industry sectors, the question is what combination of anti-leakage measure would be welfare-improving or not.

We investigate the choice of climate policy in both regions based on four potential key indicators: *i)* maximizing regional welfare, *ii)* minimizing leakage rate, *iii)* maximizing global market share for the local EITE producer, and *iv)* maximizing global market share for the local carbon-free producer. The primary objective is to understand how such variations affect the region's strategic behavior, as the region's choice may be limited when making policy decisions. For example, policymakers could be influenced by strong lobbying groups who are more concerned for their global production share than regional welfare. Or, the production of the EITE good could be of a substantially large share for the region, resulting in less flexibility for more ambitious climate policies (Sterner & Coria, 2012). As a result, the policymakers may face the problem of securing support by national interest groups, while still maintaining their national climate target (Habla & Winkler, 2013). Our simulation results suggest that the optimal strategy in the Nash Equilibrium outcomes, are also the dominant strategy for each region.

As to *i)* – maximizing region welfare – the Nash Equilibrium outcome is when the regions introduce a specific combination of OBA and consumption tax on the EITE goods. The reasoning is that consumption tax reduces the leakage and thereby increases the regional welfare to some extent. The optimal size of the OBA and consumption tax depends on the region's specific characteristics.

As to *ii)* – minimizing leakage rate –the region's emission target is fixed, and hence the leakage rate is the emission increase that occurs outside the EU and China. The Nash Equilibrium outcome is when the region introduces a 100% OBA and at least 100% consumption tax of OBA on the EITE goods. The consumption tax reduces demand, and thereby production and emissions in the unregulated region. Moreover, a combined effort to mitigate leakage from regulated regions result in a higher global emission reduction. Hence, the lowest leakage rate for both regions are obtained in the Nash Equilibrium.

As to *iii)* – maximizing global market share for the local EITE producer – the implicit production subsidy (OBA) stimulates production of the EITE good. As a result, the highest market share is obtained in the Nash equilibrium when the region allocates 100% OBA to the producer of EITE good.

As to *iv)* – maximizing global market share for the local carbon-free producer – the Nash equilibrium outcome is when the region does not supplement the ETS with an anti-leakage measure. The emission price increases the production cost for the emission-intensive producers and more demand shifts towards the carbon free good. Thus, the region achieves the highest market share in the Nash equilibrium.

The remainder of this paper is organized as follows. In section 2, we present analytically how the different policies may affect the incentives for producers and consumer. In Section 3, we provide a non-technical description of the stylized CGE model underlying our analysis of the non-cooperative policy instrument game, and present and discuss the simulation results. The model is based on Kaushal and Rosendahl (2020) and calibrated to data for the world economy. Finally, Section 4 concludes.

2. Stylized partial model analysis

In this section we show analytically, by using a stylized partial model, how emission price alone, output-based allocation, and/or consumption tax, may affect the incentives for firms and the representative consumer in the regulated regions. The model builds on the framework in Böhringer et al. (2017), and Kaushal and Rosendahl (2020).

Consider 3 regions, $j = \{1,2,3\}$, and three goods x, y, and z. Good x is emission-free and tradable, y is emission-intensive and tradable (EITE) (e.g., chemicals, metal and other minerals), and z is emission-intensive and non-tradable (e.g., electricity and transport). While produced in different regions, the same types of goods are assumed homogenous with no trade cost (for x and y). Relocating production of the y good may occur due to trade exposure, and thus OBA is considered for this sector. The market price for the goods in region j are denoted p^{xj}, p^{yj} and p^{zj}. The representative consumer's utility in region j is given by $u^j(\bar{x}^j, \bar{y}^j, \bar{z}^j)$, where the bar indicates consumption of the three goods. The utility function follows the normal assumptions.[4]

We denote the production of good x in region j as $x^j = x^{1j} + x^{2j} + x^{3j}$, where x^{ij} is produced goods in region j and sold in region i, and similarly for the y good. The production cost of goods in region j is given by $c^{xj}(x^j)$, $c^{yj}(y^j, e^{yj})$ and $c^{zj}(z^j, e^{zj})$, where e^{yj} and e^{zj} is the emission from good y and z in the region j. The cost is assumed increasing in production, i.e., c_x^{xj}, c_y^{yj}, $c_z^{zj} > 0$ (where $\frac{\partial c^{xj}}{\partial x^j} \equiv c_x^{xj}$ etc.). Further, the cost of producing good y and z is decreasing in emissions, i.e.,

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[4] Twice differentiable, increasing and strictly concave, i.e., the Hessian matrix is negative definite and we have a local maximum.

$c_e^{yj}, c_e^{zj} \leq 0$ with strict inequality when emission is regulated, cost is twice differentiable and strictly convex. All derivatives are assumed to be finite.

Supply and demand give us the following market equilibrium conditions:

$$\bar{x}^1 + \bar{x}^2 + \bar{x}^3 = x^1 + x^2 + x^3$$
$$\bar{y}^1 + \bar{y}^2 + \bar{y}^3 = y^1 + y^2 + y^3$$
$$\bar{z}^j = z^j.$$

Assume that regions 1 and 2 have implemented a cap-and-trade system, regulating emissions from production of the goods y and z:

$$\bar{E}^1 = e^{y1} + e^{z1} \qquad \bar{E}^2 = e^{y2} + e^{z2}$$

where $\bar{E}^j$ is the binding cap on total emission in region j. The emission price t^j is determined through the emission market, and there is no climate policy imposed in region 3, i.e., $t^3 = 0$.

With output-based allocation (OBA) the producers of good y receives free allowances in proportion to their output. We assume that region 1 and 2 implements OBA, in order to mitigate carbon leakage to region 3. We denote OBA with s^j to production of good y in the regulating regions. The region determines s^j with the share α^j, such that $s^j = \alpha^j t^j \left({e^{yj}}/{y^j} \right)$,[5] where the number of free allowances to producers of the y good equals the total emissions from this sector times the subsidy share. With α^j=1, we have the special case of 100% allocation of free allowances to this sector. Since good z is not trade-exposed, there is no OBA to producers of this good.

The competitive producers in region j=1,2,3 maximize profits π^j:[6]

$$Max_{x^{ij}}\, \pi_j^x = \sum_{i=1}^{3} \left[p^{xi} x^{ij} \right] - c^{xj}(x^j)$$

$$Max_{y^{ij}, e^{yj}}\, \pi_j^y = \sum_{i=1}^{3} \left[\left(p^{yi} + s^j \right) y^{ij} \right] - c^{yj}\left(y^j, e^{yj} \right) - t^j e^{yj} \tag{1}$$

$$Max_{z^j, e^{zj}}\, \pi_j^z = \left[p^{zj} z^j - c^{zj}\left(z^j, e^{zj} \right) - t^j e^{zj} \right].$$

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[5] As shown, later, in Equation (4) the unit of s^j is then e.g., US dollars ($) per produced output of y^j in region 1 and 2.

[6] To simplify notation, we replace $\sum_{i=1}^{3} x^{ij}$ with x^j in the equations.

The next case we consider an OBA combined with a consumption tax v^j on consumption of the y good, $\bar{y}^j$. Region 1 and 2 determines v^j as a share of OBA rate s^j, i.e., $v^j = \gamma^j s^j$, where γ^j is the fraction of OBA rate in region j. The representative consumer in region j maximizes utility given consumption prices and an exogenous budget restriction M^j:

$$\mathcal{L}^j = u^j\left(\bar{x}^j, \bar{y}^j, \bar{z}^j\right) - \lambda^j\left(p^x \bar{x}^j + \left(p^y + v^j\right)\bar{y}^j + p^z \bar{z}^j - M^j\right)$$

2.1. Emission price

We first consider the effects of only an emission price in region 1 and 2, i.e., t^1, $t^2 > 0$ and $s^j = v^j = 0$. Assuming interior solution, we have the following first order conditions for producer y:

$$\begin{gathered}
\frac{\partial \pi_1^y}{\partial y^1} = p^{y1} - c_y^{y1} = 0; \;\; \frac{\partial \pi_2^y}{\partial y^2} = p^{y2} - c_y^{y2} = 0; \;\; \frac{\partial \pi_3^y}{\partial y^3} = p^{y3} - c_y^{y3} = 0 \\
\frac{\partial \pi_1^y}{\partial e^{y1}} = c_e^{y1} + t^1 = 0; \;\; \frac{\partial \pi_2^y}{\partial e^{y2}} = c_e^{y2} + t^2 = 0 \\
\frac{\partial \pi_3^y}{\partial e^{y3}} = c_e^{y3} = 0
\end{gathered} \tag{2}$$

and the first order conditions for producer x and z:

$$\begin{gathered}
\frac{\partial \pi_1^x}{\partial x^1} = p^{x1} - c_x^{x1} = 0; \;\; \frac{\partial \pi_2^x}{\partial x^2} = p^{x2} - c_x^{x2} = 0; \;\; \frac{\partial \pi_3^x}{\partial x^3} = p^{x3} - c_x^{x3} = 0 \\
\frac{\partial \pi_j^z}{\partial z^j} = p^{zj} - c_z^{zj} = 0 \\
\frac{\partial \pi_1^z}{\partial e^{z1}} = c_e^{z1} + t^1 = 0; \;\; \frac{\partial \pi_2^z}{\partial e^{z2}} = c_e^{z2} + t^2 = 0 \\
\frac{\partial \pi_3^z}{\partial e^{z3}} = c_e^{z3} = 0
\end{gathered} \tag{3}$$

The interior solution requires that the prices of the two tradable goods x and y are equalized across regions, as they are homogenous with no cost of trade, i.e., we may define:[7]

$$p^x \equiv p^{xj}, \qquad p^y \equiv p^{yj}$$

The first line in Equation (2), and the first and second line in Equation (3) shows the standard first order condition, that the price for the good is equal to the marginal cost of producing that same good. In the second line in Equation (2) and third line in Equation (3), the left-hand side shows that the

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[7] This is also the case when $t^j, s^j, v^j > 0$.

marginal abatement cost of emission is equal to the emission price in region 1 and 2 for producer y and z. The third line in Equation (2) and fourth line in Equation (3) shows that the marginal abatement cost of emission is (as expected) equal to zero for the non-regulated regions. Thus, emission-intensive producers in region 1 and 2 have incentives to reduce its emissions, while producers in region 3 has no incentives to do so.

2.2. Output-based allocation

Next, we consider an OBA in region 1 and 2 such that $t^1, t^2, s^1, s^2 > 0$ and $v^j = 0$. While the first order conditions for producer of good x and z are unchanged, we now have the following first order conditions for producer y:

$$\frac{\partial \pi_1^y}{\partial y^1} = p^{y1} + s^1 - c_y^{y1} = p^{y2} + s^1 - c_y^{y1} = p^{y3} + s^1 - c_y^{y1} = 0$$

$$\frac{\partial \pi_2^y}{\partial y^2} = p^{y1} + s^2 - c_y^{y2} = p^{y2} + s^2 - c_y^{y2} = p^{y3} + s^2 - c_y^{y2} = 0$$

$$\frac{\partial \pi_3^y}{\partial y^3} = p^{y1} - c_y^{y3} = p^{y2} - c_y^{y3} = p^{y3} - c_y^{y3} = 0 \tag{4}$$

$$\frac{\partial \pi_1^y}{\partial e^{y1}} = c_e^{y1} + t^1 = 0; \quad \frac{\partial \pi_2^y}{\partial e^{y2}} = c_e^{y2} + t^2 = 0$$

$$\frac{\partial \pi_3^y}{\partial e^{y3}} = c_e^{y3} = 0$$

We see in the first and second line from Equation (4) that optimal production ensures that marginal cost of production now is equal to price for good y plus the OBA, in the regulated regions. By comparing the first order conditions in Equation (2) with Equation (4) it becomes clear that the producers in the regulated regions now receive an implicit production subsidy on top of the price for good y. Hence, the incentives to reduce emissions are now weakened for the producers of good y. Moreover, if $\alpha^j = 1$, then the producer's emissions payment is equal to zero. The first order conditions for the producer in the unregulated region is unchanged.

2.3. Consumption tax

Finally, we consider the case with OBA combined with a consumption tax on consumption of the y good, $\bar{y}^j$, i.e., $t^1,\ t^2,\ s^1,\ s^2,\ v^1,\ v^2 > 0$. We get the following first order conditions when differentiating the *Lagrangian* function for the representative consumer in region j:

$$\begin{aligned}
&\frac{\partial \mathcal{L}}{\partial \bar{x}^1} = u_{\bar{x}}^1 - p^x = 0, \quad && \frac{\partial \mathcal{L}}{\partial \bar{y}^1} = u_{\bar{y}}^1 - (p^y + v^1) = 0, \quad && \frac{\partial \mathcal{L}}{\partial \bar{z}^1} = u_{\bar{z}}^1 - p^{z1} = 0 \\
&\frac{\partial \mathcal{L}}{\partial \bar{x}^2} = u_{\bar{x}}^2 - p^x = 0, \quad && \frac{\partial \mathcal{L}}{\partial \bar{y}^2} = u_{\bar{y}}^2 - (p^y + v^2) = 0, \quad && \frac{\partial \mathcal{L}}{\partial \bar{z}^2} = u_{\bar{z}}^2 - p^{z2} = 0 \\
&\frac{\partial \mathcal{L}}{\partial \bar{x}^3} = u_{\bar{x}}^3 - p^x = 0, \quad && \frac{\partial \mathcal{L}}{\partial \bar{y}^3} = u_{\bar{y}}^3 - p^y = 0, \quad && \frac{\partial \mathcal{L}}{\partial \bar{z}^3} = u_{\bar{z}}^3 - p^{z3} = 0
\end{aligned} \tag{5}$$

assuming interior solution, and normalized the utility functions so that $\lambda^j = 1$. In region 3, $v^3 = 0$.

Without the consumption tax, the optimal consume of good y in region 1 and 2 by the representative agent is $u_{\bar{y}}^1 - p^y = 0$ and $u_{\bar{y}}^2 - p^y = 0$. By comparing this to the first order condition in Equation (5) we understand that that the consumers now will demand less of the relatively more expensive good y. Moreover, since the same types of goods are assumed homogenous, consumers will also demand less of good y from the unregulated region. Table 1 summarizes the first order conditions for good y under unilateral regulation.

[Table 1, here]

3. The numerical CGE model

The highly stylized partial analysis in Section 2 explains the economic incentives for producers and consumers. A numerical CGE analysis incorporates these incentives within an economy-wide framework, that accounts for supply and demand reactions of economic agents in a more comprehensive way and based on empirical data. The multi-sector, multi-region CGE model enables us to address policy impacts on global emissions and carbon leakage, industry-specific competitiveness, as well as economic impact of unilateral emissions regulation.

The model consists of two separate components. First, a stylized numerical CGE model that is solved for all the different policy combinations across the regions. Second, a sub model of strategic interactions between regional climate policy that determines the levels of OBA and/or consumption tax in each region.

3.1 Non-technical description of the model and data

The stylized CGE model is based on the numerical simulation model in Kaushal and Rosendahl (2020), which we extend to reflect alternative policy combinations. We follow the standard calibration procedure in CGE simulations, where the exogenous parameters are defined by base-year data. The parameterization of the model is mainly based on the World Input Output Database (WIOD), which includes national accounts on production and consumption (input-output tables) for 43 regions and 56 sectors with related CO_2-emission from each sector. For other parameters, we either use estimates from other studies or calibrate them based on simulations of a well-established large-scale CGE-model (Böhringer et al., 2017; Böhringer et al., 2018). We reconstruct the empirical data by merging the data into three regions and four sectors. We consider the following three regions in our model: the European Union/ European Economic Area (EU),[8] China (CHN) and rest of the world (ROW). We are particularly interested in the case of the EU and China, who have different emission reduction targets in their NDC and anti-leakage measure is considered for emission-intensive goods.

[Table 2, here]

Consistent with Kaushal and Rosendahl (2020), we consider the following three goods in the three regions: an emission-free and tradable x, an emission-intensive and tradable (EITE) (e.g. chemicals, metal and other minerals) y, and an emission-intensive and non-tradable (e.g. electricity and transport) z. Carbon leakage may take place through relocating production of the y good, and thus OBA is considered for this sector. These goods are produced and consumed in all of the three regions, and they can only be used in the final consumption. We also include a fourth production sector, fossil energy production f, which can only be used in energy related production y and z, and cannot be traded between regions. Hence in accordance with Böhringer et al. (2017) and Kaushal and Rosendahl (2020), we focus on the carbon leakage related to the competitive channel. The tradable goods are assumed homogenous with a global price and no transportation cost.[9]

[Table 3, here]

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[8] This includes all the 28 EU member states plus Iceland, Norway, and Liechtenstein.

[9] We also examine the effects of imperfect substitution between locally produced and imported goods in Section 3.5.

Capital, labor, fossil energy and resources are the input factors in production. Moreover, capital, labor and fossil energy are mobile between sectors but immobile between regions. The resource is only used in the fossil energy production and is immobile between regions. The producer minimizes the cost subject to technological constraints, by combining the input factors.

[Figure 1, here]

We describe the production of x, y, z as a two-level constant-elasticity-of-substitution (CES) cost functions, with the possibilities of substitution between capital, labor and fossil energy input. The two-level CES cost function for producer f consists of capital, labor and resource.

[Figure 2, here]

At the top level, we have the CES with substitution between energy/resource and value-added (capital and labor) composite. At the second level, the CES between value-added composite includes the substitution between capital and labor.[10] The emission is proportionally related to the use of energy as input for production. The emission reduction in the sectors are therefore either through; *i)* substituting energy with value-added composite, or *ii)* scaling down the production output.

The emission-free and tradable sector x accounted for 14-15% of the global CO2 emissions in 2009, according to the WIOD dataset. Hence, we set the emissions level in this sector to zero, and thus follow the same assumption from Böhringer et al. (2017) and Kaushal and Rosendahl (2020). That is, there are no carbon related emissions in sector x. Next, we measure the net exports in the tradable sectors in the base-year and incorporate the balance-of-payment constraint in the numerical model, by measuring the domestic production and consumption in each region. The calibrated emission-intensive and non-tradable sector z consists of several sectors with limited trade in the dataset. Thus, we assume that produced and consumed quantity in the same region is equal, as sector z is non-tradable.

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[10] See appendix A for summary of the CGE model.

[Table 4, here]

Finally, we define the final consumption in each region by a representative agent who maximizes utility subject to a budget constraint. The agent's utility is given as a CES combination of final consumption goods, and the budget constraint is determined by the monetary value of regional endowment of capital, labor and resource, and net revenues from emission regulation. The net revenues from emission regulation consists of emission price plus consumption tax, minus the cost of OBA. The utility maximizing agent in each region is assumed to have a CES utility function calibrated to the share form, with exogenous parameters set to base-year shares from WIOD data. Like Böhringer et al. (2017) and Kaushal and Rosendahl (2020) we set the substitution elasticity of 0.5 between goods x, y and z, with perfect substitution between locally produced and imported goods.[11]

[Figure 3, here]

3.2 Climate policy strategies

We will consider the two three regions $j = \{EU, CHN, ROW\}$, and that calibrated base-year data from 2009 is the business-as-usual (BAU) scenario. We assume no climate regulation in ROW, and that EU and CHN have already implemented a cap-and-trade system, regulating emissions from production of the goods y and z:

$$\bar{E}^{EU} = e^{yEU} + e^{zEU}, \qquad \bar{E}^{CHN} = e^{yCHN} + e^{zCHN}$$

where e^{yj} and e^{zj} is the emission from good y and z in the region j, and $\bar{E}^{j}$ is the binding cap on total emission in region j.

This is the first policy strategy (t^j) where the region j implements an emission trading system with full auctioning. t^j is the permit price in region j, determined through the emission market. The EU ETS was already in place in 2009 with the average ETS price of €13 per ton CO_2. Thus, the considered case is where an additional emission reduction target of 20 percent is set relative to the base-year emission in the EU ETS.[12] The assumption is not unreasonable as the EU has set new and more ambitious targets for 2030 and 2050 (Andresen et al., 2016). China, however, did not have an active

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[11] We also examine the effects of imperfect substitution between locally produced and imported goods in section 3.5.

[12] The reported permit price in the next chapter comes in addition to the price of €13 per ton CO_2 in 2009.

emission trading system in 2009. Here, the emission reduction target is set to 20 percent relative to base-year emission as well. As mentioned, the emission target in each region is fixed and independent of anti-leakage measures.

The second policy strategy is where region j can allocate an amount of allowances for free to the EITE industry y, i.e. OBA, in order to mitigate carbon leakage to the unregulated region. We denote OBA with s^j to production of good y in regions j. The allowances in this sector are allocated with the allocation factor α^j, ranging from 1% to 100% allocation for the industries based on output. That is, $s^j = \alpha^j t^j \left(e^{yj} / y^j \right)$ in region j, where the number of free allowances to producers of the y good equals the total emissions from this sector times the allocation factor. Since sector z is not trade-exposed, the sector does not receive allowances for free.

The third (and final) policy strategy considered is where region j can supplement the OBA with a consumption tax. Under this strategy, the consumption tax ranges from 1% to 100% as a fraction of the OBA rate s^j, i.e., $v^j = \gamma^j s^j$, where γ^j is the fraction of OBA rate in region j. Hence, different combinations of OBA allocation and consumption tax can be achieved in the numerical simulations.

The welfare in each region consists of the representative agent's utility and the environmental benefit of global emission reduction. In line with Kaushal and Rosendahl (2020) and Böhringer et al. (2017), we use the regional emission price t^j under the first policy strategy, to calculate the benefit of global emission reduction felt by each region under different policies. Since there are two emission trading systems in our model that are not linked, the emission price in each region is therefore also different. Further, the main assumption is that a global emission reduction caused by one region's action, is beneficial for the other region as well.

3.3 The sub model

We investigate the choice of climate policy in each region by looking at the following key indicators: *i)* maximizing regional welfare, *ii)* minimizing leakage rate, *iii)* maximizing global market share of y, *iv)* maximizing global market share of x, and *v)* a combination of indicators *i) – iv)*. We assume a simultaneous non-cooperative game with the two emission regulating regions, the EU and China, who choose their level of OBA and/or consumption tax based on *i)* to *v)*. We are particularly interested in this set-up to understand how such variations affect the region's strategic behavior, as the region's choice may be limited when making policy decisions. The Nash Equilibrium outcome of this game is the region's best response to the actions of the other region (Varian, 2010). To simulate all the outcomes, the stylized CGE model is run 40401 times (for each indicator) with different combination of policies in each region. Then, the sub model constructs a pay-off matrix for each indicator (with all the 40401 outcomes) and solves the Nash Equilibrium outcome.

3.4 Numerical results

[Table 5, here]

Results in Table 5 shows the effect on welfare in EU and China in the presence of different combination of policies, i.e., indicator *i)*. The regional welfare is defined as the money-metric utility of consumption minus the valuation of changes in global emissions. Policy choices by the EU are on the right and China's on the left, in the brackets. t^{EU} and t^{CHN} is the scenario with only emission price in the EU and China respectively. s and v with percent values is the correspondingly allocation factor in sector y of OBA, and consumption tax rate as a fraction of OBA.[13] The change is displayed as a percentage change compared to the BAU scenario, also considering the change in global emissions, where we use the emission price to value these changes. As described earlier, we us the regional emission prices, without any supplementing policies, to value the changes in global emissions for each region. For $j = \{EU, CHN\}$ the numerical simulation suggests a valuation of t^{EU} = \$99.64 for EU, and t^{CHN} = \$78.39 for China, per ton of CO_2. That is, the abatement cost in the EU is greater than in China.

The result shows that the optimal strategy when both regions maximizes welfare is to supplement OBA with a consumption tax on the EITE good, i.e., our Nash Equilibrium. This outcome is in line with previous results (Böhringer et al., 2017; Kaushal & Rosendahl, 2020) since a consumption tax reduces the leakage and thereby increases the regional welfare. The Nash Equilibrium outcome is $s_{43\%}v_{80\%}$ for China and $s_{72\%}v_{100\%}$ for the EU. A likely reason for the lower optimal OBA in China is the lower abatement cost compared to the EU, and China's higher emission intensity in sector y (see Table 4). The EU is the only net exporter of good x and therefore the higher consumption tax rate is optimal in the EU. Table 5 further suggests that if one region's policy is kept fixed, their welfare increases when another region introduces a combination of OBA with a consumption tax. The main

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[13] E.g., with $s_{72\%}v_{100\%}$, we have α = 0.72 and $v = s$.

driver for the welfare increase is the reduction in leakage rate which benefits both regions. The numerical simulation suggests that the optimal rate is unaffected by an introduction of supplementing policy in the other region. That is, the optimal strategy in the Nash Equilibrium outcome, is also the dominant strategy for the regions. The largest welfare effect compared to the BAU scenario for China is approximately 0.60%. In this case, China's policy is $s_{43\%}v_{80\%}$, meanwhile the EU's is $s_{100\%}v_{100\%}$. The largest welfare effect for the EU is around 0.41% if they choose $s_{72\%}v_{100\%}$ and China choose $s_{100\%}v_{100\%}$.

The leakage rate is defined as percentage changes in non-abating region's (ROW) emission, over the emission reduction in the regulating region's emission (EU and China). Here, the BAU emission is the baseline.[14] A positive (negative) number results in a positive (negative) leakage rate. Given no energy trade in our model, leakage only happens through the market for EITE-goods (y). Introducing OBA has significant impact on leakage.[15] That is, OBA provides a perfect leakage mitigation tool in the model, in line with Kaushal and Rosendahl (2020). The impact is particularly greater when the EU introduces OBA, which almost fully eliminates the leakage. This reflects the crucial fact that abatement cost in EU is greater than in China. With consumption tax, the leakage rate continues to decrease. The results suggest a Nash Equilibrium outcome with 100% OBA and consumption tax to at least 100% of OBA for both regions, i.e., $s_{100\%}v_{100\%}$. The consumption tax reduces demand for EITE good, and thus production and emissions in the unregulated region. Hence, in Nash Equilibrium, given indicator *ii)*, both regions supplement the 100% OBA with a 100% consumption tax on the EITE good.

The highest leakage rate of around 39.8% is obtained when no complementing policies are introduced in the regulating regions. The lowest leakage rate is obtained in the Nash Equilibrium (around -8% leakage rate). The result suggests a combined effort to mitigate leakage from the regulating regions, in order to achieve a higher global emission reduction. That is, at least a 100% OBA combined with a 100% consumption tax by both regions could be used strategically in order to reduce GHG emissions from unregulated region (ROW) even further than BAU scenario.

In accordance with earlier papers, we referred to OBA as an implicit production subsidy for the EITE producer. If the region's main indicator had been to maximize the net production of this good, the result would consequently also have been to supplement their ETS with 100% OBA. An interesting approach is to observe the global market share of the EITE good, since the producers could - at least

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[14] Since the regulated regions are only concerned of the increase emissions in the non-abating region, we express the leakage rate as $\frac{\Delta(E^{ROW})}{-\Delta(E^{EU}+E^{CHN})}$, where $E^j = e^{y^j} + e^{z^j}$.

[15] See Appendix B, Table 10

- compromise on maintaining the market share as the net global demand for the EITE good declines. The highest market share of the EITE producer is obtained when a region allocates at least 100% OBA to the producer of EITE-good, which is also the Nash Equilibrium.[16] Hence, given indicator *iii)*, the regions would supplement their ETS with at least 100% OBA. The market share in the Nash equilibrium is approximately 22.1% for China and 21.8% for the EU. The highest market shares a region can obtain in this game, is when only that region supplements the ETS with OBA. Hence, this strategy for EU and China is also the dominant strategy. The market shares for both regions are greater than in BAU scenario. In the BAU scenario, the result suggests a market share of approximately 20.7% for both regions.

[Table 6, here]

If both regions maximize global market shares of the emission-free and tradable good x, indicator *iv)*, Table 6 shows that the they would not supplement their ETS with any anti-leakage measure. The emission price increases the production cost for the emission-intensive good y and z. More demand shifts towards the relatively cheaper good x, and thereby the production of the same good increases as well. In this Nash Equilibrium, the regions achieve a higher market share of good x (12.3% for China and 31.5% for the EU) than in the BAU scenario (10.7% for China and 29.7% for the EU). The strategies in this Nash equilibrium outcome are also the dominant strategies for the regions. The share of good x for one region increases when another region introduces OBA to at least 100%. However, the share decreases somewhat if the OBA is combined with a consumption tax.

To sum up, we present all the Nash Equilibrium outcomes from the numerical analysis in Table 7, as well as the outcomes with other combinations of indicators. The EU's indicators are listed on the right, and China's on the left, in the brackets. The table, again, shows that the region's strategy in the Nash Equilibrium outcome is also the dominant strategy for the region. That is, for a given indicator, the region chooses the same strategy independent of the other region's choice.

[Table 7, here]

3.5 Sensitivity analysis

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[16] See Appendix B, Table 11

To check to what degree the numerical results are robust, we now examine the effects of changing some of the main assumptions. We first relax the assumption that goods produced in different regions are homogenous, and assume that domestic and foreign goods are distinguished by origin. Next, we keep the same assumptions from our benchmark simulation, but assume that the substitution elasticity for the representative agent is set to 2. Finally, we test for a different marginal social damage cost than the emission price to calculate the environmental benefit of global emission reduction.

First, consider the effects of relaxing the assumption that goods produced in different regions are homogenous. We follow the heterogeneous goods approach by Armington (1969) when distinguish between domestic and foreign produced goods ("Armington goods"). We keep the same assumption at the top level of the utility function, when substituting between the goods x, y and z. At the second level, we include substitution between domestic and imported goods x and y, and finally at the third level we distinguish between the origins of the foreign produced goods. We assume a substitution of elasticity at the top level of 0.5 (as before), at the second level of 4, and at the third level of 8.[17]

[Table 8, here]

In Table 8 we show how this assumption affects the Nash Equilibrium outcomes. The welfare effects under all the different policy combination are higher with Armington goods than with the homogenous goods. Mainly, this is a result of further limited leakage than with homogenous goods, and hence the benefits of emission reductions are bigger. Compared with Table 7, the only different strategy in a Nash Equilibrium outcome is when the region maximizes welfare. The OBA and consumption tax rate is higher with Armington goods assumption $(s_{100}^{CHN} v_{100}^{CHN}, s_{100}^{EU} v_{100}^{EU})$ than with homogenous goods assumption $(s_{43}^{CHN} v_{80}^{CHN}, s_{72}^{EU} v_{100}^{EU})$. The welfare improves monotonically with the consumption tax to at least 100% of the OBA rate for both regions, with Armington goods. With indicator *ii)*, *iii)* or *iv)* assuming Armington goods, the results show the same outcome as the benchmark simulation. Like in the benchmark simulation, the choice of strategy in the Nash Equilibrium outcomes in Table 8 are also the dominant strategies for the region.

[Table 9, here]

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[17] The heterogeneous goods case transforms into the case of homogenous goods with an infinite Armington elasticity setting on the second and third levels.

We go back to the homogenous good assumption for the next tests. Table 9 shows the effects of alternative combinations of substitution elasticity for the representative agent. That is, we change the substitution elasticity for the representative agent from 0.5 to 2. The tests are conducted with substitution elasticity change in all the three regions. With higher substitution elasticity, the Nash Equilibrium outcome given indicator *i)* is $(s_{34}^{CHN} v_{64}^{CHN}, s_{61}^{EU} v_{98}^{EU})$. The OBA rate for EU and consumption tax rate for China is lower than in the benchmark simulation. Without any anti-leakage measure a higher substitution elasticity (of 2) tends to shift consumption more towards the carbon-free good x, and to x and z with a consumption tax combined with OBA. Hence, the welfare gains of an anti-leakage measure in EU and China are in general lower compared to our baseline simulations. Thus, a lower OBA and consumption tax is needed in the EU and China (respectively). However, a consumption tax combined with OBA still has a welfare improving effect. The welfare improvement compared to BAU scenario are in general higher with higher substitution elasticity, as the leakage rate is lower. We can see from Table 9 that the tests support the findings from our analysis in section 3.4 for indicator *ii)*, *iii)* and *iv)*. Here as well, the strategies in the Nash Equilibrium outcome are dominant strategies for the region.

In the benchmark simulation we used the regional emission price under the first policy strategy to calculate the benefit of global emission reduction felt by each region under different policies. However, it is also the possibility of this value being different than the observed regional emission price under the scenario without supplementing policies to the ETS. In the EU ETS for instance, the emission price has been fairly low over the last years. Thus, one could argue that the valuation is higher than the current CO_2 price. First, we test for a valuation that is 50 % higher (in EU and China) than the estimated carbon price from section 3.4. The benefits of the climate policy would be bigger as global emission reductions would have a greater impact on welfare. As a result, the optimal OBA and consumption tax, in both regions, is higher than with our benchmark assumption $(s_{51}^{CHN} v_{82}^{CHN}, s_{86}^{EU} v_{100}^{EU})$. Next, we test for the valuation being the same in both regions. Here we use the global Social Cost of Carbon (SCC) estimate based on meta-analysis by Wang et al. (2019). Their estimate of the SCC equals to \$54.70/t CO_2, which is lower than both China's and the EU's valuation in our benchmark simulation. Now, the benefits of the climate policy would be smaller as global emission reductions would have a smaller impact on welfare. This results in a lower optimal OBA and consumption tax for both regions $(s_{38}^{CHN} v_{77}^{CHN}, s_{61}^{EU} v_{100}^{EU})$. Nevertheless, the consumption tax is still 100% of the OBA rate in the EU as the region is the only net exporter of the carbon free good.

4. Concluding remarks

China will rely on its emission trading system (ETS), in order to achieve their nationally determined contribution (NDC) from the Paris climate agreement. Together, the EU ETS and the Chinese ETS will be the world's largest emissions trading systems in terms of regulated emissions (Böhringer et al., 2018). As rest of the world closely follows the unilateral initiatives by the EU and China, the policymakers in both regions are well aware that their unilateral action leads to carbon leakage without a global initiative to reduce greenhouse gas (GHG) emissions. There are numerous approaches in the economic literature to mitigate carbon leakage. A very common anti-leakage measure in an ETS is output-based allocation (OBA) to emission-intensive and trade-exposed (EITE) industries. OBA, however, works as an implicit production subsidy to domestic production of EITE goods. Hence, an approach to supplement OBA with a consumption tax on all use of EITE goods have been proposed (Böhringer et al., 2017; Kaushal & Rosendahl, 2020). In the current paper, we have examined the choice of climate policy instrument for a region, in the presence of another region’s climate policy. In particular, we have looked into the case when regions can choose to supplement their ETS with different combinations of OBA and/or with a consumption tax, in the presence of another regulating region.

We examined the choice of policy instrument for two separate regions with a stylized computable general equilibrium (CGE) model calibrated to real world data, where we considered the situation of the EU ETS and the Chinese ETS. We then assessed the Nash Equilibrium outcomes in a non-cooperative game of policy instruments, by combining the CGE model with a sub-model. We presented the choice of climate policy in both regions based on the following indicators: *i)* maximizing regional welfare, *ii)* minimizing leakage rate *iii)* maximizing global market share for the producer of the EITE good, *iv)* maximizing global market share for the producer of the carbon-free good, and *v)* a combination of indicators *i) – iv).*

The simulation showed that depending on the choice of indicator, the regions would choose different variation of policy combinations. In the context of maximizing regional welfare, however, both regions would in the Nash Equilibrium outcome implement a consumption tax on top of the OBA. In particular, the welfare for both the EU and China were consistently improved with a specific combination of OBA with consumption tax, irrespective of the other regions choice of climate policy. The results showed that the strategy in the Nash Equilibrium outcome was also the dominant strategy for the regions. The numerical simulation also showed that OBA combined with consumption tax had a significant impact on the leakage rate. Moreover, the impact was even stronger with a combined effort by both regions.

Böhringer et al. (2017) and Kaushal and Rosendahl (2020) found that combining output-based allocation with a consumption tax may result in regional welfare improving effect. However, in the current situation in which there are many separated carbon emission trading systems globally, one region's choice of climate policy could affect another region's choice of climate policy. Our analysis suggest that output-based allocation combined with a consumption tax could be used strategically by regulated regions in order to reduce emissions in unregulated regions. Moreover, an interesting insight in this paper is that our results also support the findings of the previous two papers. That is, in terms of welfare improvement the region would complement its ETS with an output-based allocation and a consumption tax, even in the presence of other region's climate policies.

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Tables

	Emission Price	OBA	OBA + Consumption tax
Production	$p^y = c_y^{y1}$; $p^y = c_y^{y2}$; $p^y = c_y^{y3}$	$p^y + s^1 = c_y^{y1}$; $p^y + s^2 = c_y^{y2}$; $p^y = c_y^{y3}$	$p^y + s^1 = c_y^{y1}$; $p^y + s^2 = c_y^{y2}$; $p^y = c_y^{y3}$
Abatement	$-c_e^{y1} = t^1$ $-c_e^{y2} = t^2$ $c_e^{y3} = 0$	$-c_e^{y1} = t^1$ $-c_e^{y2} = t^2$ $c_e^{y3} = 0$	$-c_e^{y1} = t^1$ $-c_e^{y2} = t^2$ $c_e^{y3} = 0$
Consumption	$u_{\bar{y}}^{j} = p^y$	$u_{\bar{y}}^{j} = p^y$	$u_{\bar{y}}^{1} = p^y + v^1$; $u_{\bar{y}}^{2} = p^y + v^2$; $u_{\bar{y}}^{3} = p^y$

Table 1: First-order conditions for good y under unilateral regulation.

Model Regions	**WIOD Regions**
EU: European Union/ European Economic Area	Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Spain, Sweden, United Kingdom
China	China
ROW: Rest of the world	Australia, Brazil, Canada, India, Indonesia, Japan, Mexico, Russia, Rest of the world, South Korea, Taiwan, Turkey, United States

Table 2: Mapping of World Input Output Database (WIOD) regions to model regions

Model Sectors	**WIOD Sectors**
y: emission-intensive and tradable goods	Oil, Mining and Quarrying; Chemicals and Chemical Products; Basic Metals and Fabricated Metal; Other Non-Metallic Mineral; Transport Equipment; Textiles and Textile Products; Food; Beverages and Tobacco; Pulp Paper; Paper, Printing and Publishing
z: emission-intensive and non-tradable goods	Transport Sector (air, water, rail, road); Electricity
x: emission-free and tradable goods	All remaining goods and services

Table 3: Mapping of WIOD sectors to model sectors

	Production (billion $)	***Consumption (billion $)***	***CO_2 (billion ton)***
x^{EU}	*25 066*	*24 610*	-
y^{EU}	*5 025*	*5 111*	*0.90*
z^{EU}	*1 998*	*1 998*	*1.78*
x^{CHN}	*9 059*	*8 786*	-
y^{CHN}	*5 030*	*5 020*	*2.11*
z^{CHN}	*949*	*949*	*3.60*
x^{ROW}	*51 101*	*51 830*	-
y^{ROW}	*14 271*	*14 194*	*4.21*
z^{ROW}	*4 871*	*4 871*	*8.24*

Table 4: Base-year WIOD data values and calibrated parameters in the numerical model

		EU			
		t^{EU}	$s_{72}^{EU}\,v_{100}^{EU}$	s_{100}^{EU}	$s_{100}^{EU}v_{100}^{EU}$
CHN	t^{CHN}	*(0.14%, 0.19%)*	*(0.41%, 0.25%)*	*(0.57%, 0.19%)*	*(0.57%, 0.19%)*
	$s_{43}^{CHN}\,v_{80}^{CHN}$	*(0.18%, 0.23%)*	*(0.39%, 0.30%)*	*(0.59%, 0.24%)*	*(0.60%, 0.25%)*
	s_{100}^{CHN}	*(-0.07%, 0.35%)*	*(0.15%, 0.41%)*	*(0.36%, 0.39%)*	*(0.36%, 0.39%)*
	$s_{100}^{CHN}\,v_{100}^{CHN}$	*(-0.07%, 0.35%)*	*(0.15%, 0.41%)*	*(0.36%, 0.39%)*	*(0.36%, 0.39%)*

Table 5: China and the EU's welfare effect with different combinations of policies in the EU and China.

		EU			
		t^{EU}	$s_{72}^{EU}\,v_{100}^{EU}$	s_{100}^{EU}	$s_{100}^{EU}v_{100}^{EU}$
CHN	t^{CHN}	*(12.3%, 31.5%)*	*(12.6%, 29.5%)*	*(12.8%, 27.7%)*	*(12.8, 27.7%)*
	$s_{43}^{CHN}\,v_{80}^{CHN}$	*(11.6%, 31.7%)*	*(11.9%, 29.8%)*	*(12.2%, 28%)*	*(12.2%, 28.1%)*
	s_{100}^{CHN}	*(9.6%, 32.2%)*	*(10%, 30.7%)*	*(10.3%, 29.1%)*	*(10.3%, 29.2%)*
	$s_{100}^{CHN}\,v_{100}^{CHN}$	*(9.6%, 32.2%)*	*(10%, 30.7%)*	*(10.4%, 29.1%)*	*(10.4%, 29.2%)*

Table 6: China's and the EU's global market share of non-carbon good x with different combinations of policies in the EU and China.

		EU			
		i)	*ii)*	*iii)*	*iv)*
CHN	*i)*	$\left(s_{43}^{CHN}\,v_{80}^{CHN}, s_{72}^{EU}\,v_{100}^{EU}\right)$	$\left(s_{43}^{CHN}\,v_{80}^{CHN}, s_{100}^{EU}v_{100}^{EU}\right)$	$\left(s_{43}^{CHN}\,v_{80}^{CHN}, s_{100}^{EU}\right)$	$\left(s_{43}^{CHN}\,v_{80}^{CHN}, t^{EU}\right)$
	ii)	$\left(s_{100}^{CHN}\,v_{100}^{CHN}, s_{72}^{EU}\,v_{100}^{EU}\right)$	$\left(s_{100}^{CHN}\,v_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU}\right)$	$\left(s_{100}^{CHN}\,v_{100}^{CHN}, s_{100}^{EU}\right)$	$\left(s_{100}^{CHN}\,v_{100}^{CHN}, t^{EU}\right)$
	iii)	$\left(s_{100}^{CHN}, s_{72}^{EU}\,v_{100}^{EU}\right)$	$\left(s_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU}\right)$	$\left(s_{100}^{CHN}, s_{100}^{EU}\right)$	$\left(s_{100}^{CHN}, t^{EU}\right)$
	iv)	$(t^{CHN}, s_{72}^{EU}\,v_{100}^{EU})$	$(t^{CHN}, s_{100}^{EU}v_{100}^{EU})$	(t^{CHN}, s_{100}^{EU})	(t^{CHN}, t^{EU})

Table 7: Summary of the Nash equilibriums and dominant strategies based on indicators i) – iv).

		EU			
		i)	*ii)*	*iii)*	*iv)*
CHN	*i)*	$\left(s_{100}^{CHN}\,v_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU}\right)$	$\left(s_{100}^{CHN}\,v_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU}\right)$	$(s_{100}^{EU}v_{100}^{EU}, s_{100}^{EU})$	$(s_{100}^{EU}v_{100}^{EU}, t^{EU})$
	ii)	$\left(s_{100}^{CHN}\,v_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU}\right)$	$\left(s_{100}^{CHN}\,v_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU}\right)$	$\left(s_{100}^{CHN}\,v_{100}^{CHN}, s_{100}^{EU}\right)$	$\left(s_{100}^{CHN}\,v_{100}^{CHN}, t^{EU}\right)$
	iii)	$\left(s_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU}\right)$	$\left(s_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU}\right)$	$\left(s_{100}^{CHN}, s_{100}^{EU}\right)$	$\left(s_{100}^{CHN}, t^{EU}\right)$
	iv)	$(t^{CHN}, s_{100}^{EU}v_{100}^{EU})$	$(t^{CHN}, s_{100}^{EU}v_{100}^{EU})$	(t^{CHN}, s_{100}^{EU})	(t^{CHN}, t^{EU})

Table 8: Summary of Nash equilibriums based on indicators *i) – iv)*, assuming Armington goods.

		EU			
		i)	*ii)*	*iii)*	*iv)*
CHN	*i)*	$(s_{34}^{CHN}v_{64}^{CHN}, s_{61}^{EU}v_{98}^{EU})$	$(s_{34}^{CHN}v_{64}^{CHN}, s_{100}^{EU}v_{100}^{EU})$	$(s_{34}^{CHN}v_{64}^{CHN}, s_{100}^{EU})$	$(s_{34}^{CHN}v_{64}^{CHN}, t^{EU})$
	ii)	$(s_{100}^{CHN}v_{100}^{CHN}, s_{61}^{EU}v_{98}^{EU})$	$(s_{100}^{CHN}v_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU})$	$(s_{100}^{CHN}v_{100}^{CHN}, s_{100}^{EU})$	$(s_{100}^{CHN}v_{100}^{CHN}, t^{EU})$
	iii)	$(s_{100}^{CHN}, s_{61}^{EU}v_{98}^{EU})$	$(s_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU})$	$(s_{100}^{CHN}, s_{100}^{EU})$	(s_{100}^{CHN}, t^{EU})
	iv)	$(t^{CHN}, s_{61}^{EU}v_{98}^{EU})$	$(t^{CHN}, s_{100}^{EU}v_{100}^{EU})$	(t^{CHN}, s_{100}^{EU})	(t^{CHN}, t^{EU})

Table 9: Summary of Nash equilibriums based on indicators *i) – iv)*, of alternative substitution elasticity.

Figures

Elasticities: $\sigma_{KLE} = 0.5$ $\sigma_{KL} = 1$

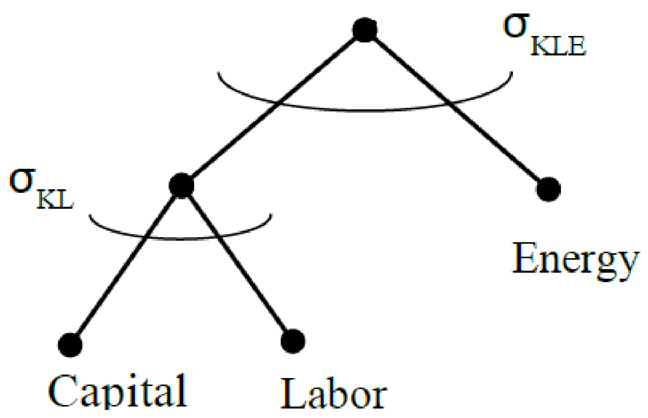

Figure 1: Nesting in production, except for fossil fuel energy

Elasticities: $\sigma_Q = 0.9$ $\sigma_{KL} = 1$

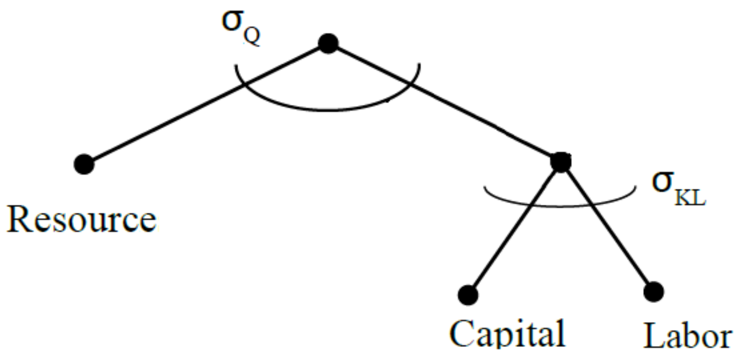

Figure 2: Nesting in production of fossil fuel energy

Elasticity: $\sigma_W = 0.5$

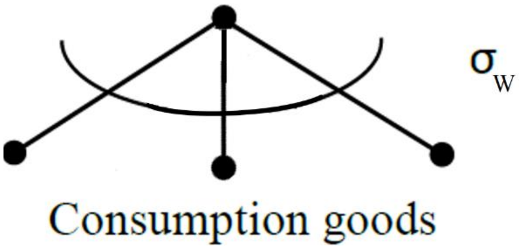

Figure 3: Nesting in consumption

Appendix A, Summary of the numerical CGE model

Indices and sets:

Set of regions	R	EU, CHN, ROW
Set of goods	g	x, y, z
r (alias j)		Index for regions

Variables:

S^{gr}	Production of good g in r
S^{r}_{FE}	Production of fossil energy (FE) in r
D^{gr}	Aggregated consumer demand of good g in r
KL^{gr}	Value-added composite for g in r
KLF^{r}	Value-added composite for FE in r
A^{gr}	Armington aggregate of g in r
IM^{gr}	Import aggregate of g in r
W^{r}	Consumption composite in r

$p^{g,r}$	Price of g in r
p^{r}_{FE}	Price of Primary fossil FE in r
p^{gr}_{KL}	Price of value added for g in r
p^{r}_{KLF}	Price of value added for FE in r
p^{r}_{L}	Price of labor (wage rate) in r
p^{r}_{K}	Price of capital (rental rate) in r
p^{r}_{Q}	Rent for primary energy resource in r
p^{gr}_{A}	Price of Armington aggregate of g in r
p^{gr}_{IM}	Price of aggregate imports of g in r
p^{r}_{CO2}	Price of CO2 emission in r
p^{r}_{W}	Price of consumption composite in r
o^{gr}	Output-Based Allocation on g in r
v^{gr}	Consumption tax on g in r

Parameters:

σ_{KLE}^{r}	Substitution between value-added and energy g in r
σ_{KL}^{r}	Substitution between value-added g in r
σ_{Q}^{r}	Substitution between value-added and natural resource in FE in r
σ_{LN}^{r}	Substitution between value-added in FE in r
σ_{A}^{gr}	Substitution between import and domestic g in r
σ_{IM}^{gr}	Substitution between imports from different g in r
σ_{W}^{r}	Substitution between goods to consumption

θ_{FE}^{gr}	Cost Share of FE in production of g in r
θ_{KL}^{gr}	Cost Share of labor in production of g in r
θ_{Q}^{r}	Cost Share of natural resource in production of FE in r
θ_{LN}^{r}	Cost Share of labor in production of FE in r
θ_{A}^{gr}	Cost Share of domestic goods g in consumption in r
θ_{IM}^{gr}	Cost Share of different imports goods g in consumption in r

L_{0}^{gr}	Labor endowment in sector g in region r
$L_{0,FE}^{r}$	Labor endowment in FE in region r
K_{0}^{gr}	Capital endowment in sector g in region r
$K_{0,FE}^{r}$	Capital endowment in FE in region r
Q_{0}^{r}	Resource endowment of primary fossil energy in region r
$CO2_{MAX}^{r}$	CO_2 emission allowance in region r
κ_{CO2}^{r}	Coefficient for primary fossil energy of CO_2 emission in region r

Zero Profit Conditions

Production of goods except for fossil primary energy:

$$\pi_{S}^{gr} = \left(\theta_{FE}^{gr}\left(p_{FE}^{r} + \kappa_{CO2}^{r} p_{CO2}^{gr}\right)^{(1-\sigma_{KLE}^{r})} + \left(1-\theta_{FE}^{gr}\right) p_{KL}^{gr\,(1-\sigma_{KLE}^{r})}\right)^{\left(\frac{1}{1-\sigma_{KLE}^{r}}\right)} \geq p^{gr} + o^{gr}$$

$$\perp S^{gr}$$

Sector specific value-added aggregate for x, y and z:

$$\pi_{KL}^{gr} = \left(\theta_{KL}^{gr} p_L^{r\,(1-\sigma_{KL}^{gr})} + (1-\theta_{KL}^{gr}) p_K^{r\,(1-\sigma_{KL}^{gr})}\right)^{\left(\frac{1}{1-\sigma_{KL}^{gr}}\right)} \geq p_{KL}^{gr} \qquad \perp KL^{gr}$$

Production of fossil primary energy:

$$\pi_{FE}^{r} = \left(\theta_{Q}^{r} p_Q^{r\,(1-\sigma_{Q}^{r})} + (1-\theta_{Q}^{r}) p_{KLF}^{r\,(1-\sigma_{Q}^{r})}\right)^{\left(\frac{1}{1-\sigma_{Q}^{r}}\right)} \geq p_{FE}^{r} \qquad \perp S_{FE}^{r}$$

Sector specific value-added aggregate for FE:

$$\pi_{KLF}^{r} = \left(\theta_{LN}^{r} p_L^{r\,(1-\sigma_{LN}^{r})} + (1-\theta_{LN}^{r}) p_K^{r\,(1-\sigma_{LN}^{r})}\right)^{\left(\frac{1}{1-\sigma_{LN}^{r}}\right)} \geq p_{KLF}^{r} \qquad \perp KLF^{r}$$

Armington aggregate except for FE:

$$\pi_{A}^{gr} = \left(\theta_{A}^{gr} (p^{gr} + v^{gr})^{(1-\sigma_{A}^{gr})} + (1-\theta_{A}^{gr}) p_{IM}^{gr\,(1-\sigma_{A}^{gr})}\right)^{\left(\frac{1}{1-\sigma_{A}^{gr}}\right)} \geq p_{A}^{gr} \qquad \perp A^{gr}$$

Import Composite except for FE:

$$\pi_{IM}^{gr} = \left(\sum_{j\neq r} \theta_{IM}^{gjr} \left(p^{gj} + v^{gr}\right)^{(1-\sigma_{IM}^{gr})}\right)^{\left(\frac{1}{1-\sigma_{IM}^{gr}}\right)} \geq p_{IM}^{gr} \qquad \perp IM^{gr}$$

Consumption composite:

$$\pi_{W}^{r} = \left(\theta_{W}^{xr} p_A^{xr\,(1-\sigma_{W}^{r})} + \theta_{W}^{yr} p_A^{yr\,(1-\sigma_{W}^{r})} + \theta_{W}^{zr} p_A^{zr\,(1-\sigma_{W}^{r})}\right)^{\left(\frac{1}{1-\sigma_{W}^{r}}\right)} \geq p_{W}^{r} \qquad \perp W^{r}$$

Market Clearing Conditions

Labor:

$$\sum_g L_0^{gr} + L_{0,FE}^{r} \geq \sum_g KL^{gr} \frac{\partial \pi_{KL}^{gr}}{\partial p_L{}^{r}} + KLF^{r} \frac{\partial \pi_{KLF}^{r}}{\partial p_L{}^{r}} \qquad \perp p_L{}^{r}$$

Capital:

$$\sum_g K_0^{gr} + K_{0,FE}^{r} \geq \sum_g KL^{gr} \frac{\partial \pi_{KL}^{gr}}{\partial p_K{}^{r}} + KLF^{r} \frac{\partial \pi_{KLF}^{r}}{\partial p_K{}^{r}} \qquad \perp p_K{}^{r}$$

Primary fossil energy resource:

$$Q_0^r \geq S_{FE}^r \frac{\partial \pi_{FE}^r}{\partial p_Q^r} \qquad \perp p_Q{}^r$$

Value-added except FE:

$$KL^{gr} \geq S^{gr} \frac{\partial \pi_S^{gr}}{\partial p_{KL}^{gr}} \qquad \perp p_{KL}^{gr}$$

Value-added FE:

$$KLF^r \geq S_{FE}^r \frac{\partial \pi_{FE}^r}{\partial p_{KLF}^r} \qquad \perp p_{KLF}^r$$

Armington Aggregate:

$$A^{gr} \geq W^r \frac{\partial \pi_W^r}{\partial p_A^{gr}} \qquad \perp p_A^{gr}$$

Import Aggregate:

$$IM^{gr} \geq A^{gr} \frac{\partial \pi_A^{gr}}{\partial p_{IM}^{gr}} \qquad \perp p_{IM}^{gr}$$

Supply-demand balance of goods, except FE:

$$S^{gr} \geq A^{gr} \frac{\partial \pi_A^{gr}}{\partial p^{gr}} + \sum_{j \neq r} IM^{gj} \frac{\partial \pi_{IM}^{gj}}{\partial p^{gj}} \qquad \perp p^{gr}$$

Supply-demand balance of FE:

$$S_{FE}^r \geq \sum_g S^{gr} \frac{\partial \pi_S^{gr}}{\partial \left(p_{FE}^r + \kappa_{CO2}^r p_{CO2}^{gr}\right)} \qquad \perp p_{FE}^r$$

Demand of goods:

$$D^{gr} \geq A^{gr} \frac{\partial \pi_A^{gr}}{\partial p^{gr}} + IM^{gr} \frac{\partial \pi_{IM}^{gr}}{\partial p^{gr}} \qquad \perp D^{gr}$$

CO$_2$ Emission in region:

$$CO2_{MAX}^r \geq \kappa_{CO2}^r S_{FE}^r \qquad \perp p_{CO2}^r$$

Consumption by consumers

$$p_W^r W^r \geq p_L^r \left(\sum_g L_0^{gr} + L_{0,FE}^r \right) + p_K^r \left(\sum_g K_0^{gr} + K_{0,FE}^r \right) + p_Q{}^r Q_0^r + p_{CO2}^r CO2_{MAX}^r - S^{gr} o^{gr}$$
$$+ D^{gr} v^{gr} \qquad \perp p_W^r$$

Appendix B: Tables

		EU			
		t^{EU}	$s_{72}^{EU} v_{100}^{EU}$	s_{100}^{EU}	$s_{100}^{EU} v_{100}^{EU}$
CHN	t^{CHN}	*39.8%*	*21%*	*4%*	*3.7%*
	$s_{43}^{CHN} v_{80}^{CHN}$	*33.7%*	*16.7%*	*0.9%*	*0.6%*
	s_{100}^{CHN}	*18.1%*	*5.4%*	*-7.5%*	*-7.7%*
	$s_{100}^{CHN} v_{100}^{CHN}$	*17.6%*	*4.9%*	*-7.8%*	*-8%*

Table 10: Leakage rate with different combinations of policies in the EU and China.

		EU			
		t^{EU}	$s_{72}^{EU} v_{100}^{EU}$	s_{100}^{EU}	$s_{100}^{EU} v_{100}^{EU}$
CHN	t^{CHN}	*(14.9%, 13.4%)*	*(14.0%, 20.5%)*	*(13.1%, 27%)*	*(13.1, 26.9%)*
	$s_{43}^{CHN} v_{80}^{CHN}$	*(17.6%, 12.7%)*	*(16.5%, 19.3%)*	*(15.4%, 25.7%)*	*(15.5%, 25.5%)*
	s_{100}^{CHN}	*(24.8%, 10.8%)*	*(23.5%, 16.2%)*	*(22.1%, 21.8%)*	*(22.2%, 21.6%)*
	$s_{100}^{CHN} v_{100}^{CHN}$	*(24.7%, 10.8%)*	*(23.4%, 16.1%)*	*(22.1%, 21.7%)*	*(22.1%, 21.6%)*

Table 11: China's and the EU's global market share of the EITE good with different combinations of policies in the EU and China.