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Abstract:

Unilateral actions to reduce CO2 emissions can be costly and may lead to carbon leakage through relocation of emission-intensive and trade-exposed industries (EITE). This paper examines the welfare effects of introducing an emission offset mechanism for the EITE sector, where EITE producers may have to acquire more than one offset credit to balance one ETS allowance. The analytical results suggest that under certain conditions it is globally welfare improving for a single region to introduce such an offset mechanism. Numerical simulations in the context of the EU ETS and REDD+ credits support the analytical findings, and suggest that it is optimal for the EU to require EITE producers to acquire several REDD+ credits to offset one EU ETS allowance.

Key words: Carbon leakage; emission trading system; unilateral policy; REDD+

JEL classification: D61, F18, H23, Q54

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1. Introduction

In order to reduce emissions of greenhouse gases (GHGs), many countries (and regions) consider or have introduced unilateral climate policies such as emissions trading systems (ETS). However, unilateral action raises at least two types of concerns. First, the cost of action is higher than necessary as cheap mitigation options in unregulated regions are forgone. Second, the climate policy may lead to carbon leakage, such as relocation of emission-intensive and trade-exposed industries (EITE) to unregulated regions,[1] reducing the effectiveness of the unilateral policy. The two concerns are related – the more costly unilateral action is, the higher is typically leakage. As a response to these concerns, emission trading is often supplemented with access to offsets and free allocation of emission allowances.

In the context of the EU and its emission trading system (EU ETS), the abatement cost is generally greater than in other regions, and carbon leakage is of great concern.[2] To prevent leakage, the EU hands out a large number of free allowances to the firms, and there is a large literature analyzing this (e.g., Martin et al., 2014; Fischer and Fox, 2012; Böhringer et al., 2017).

Regarding offsets, firms regulated by the EU ETS have had the option to use CDM (Clean Development Mechanism) credits to offset some of their emissions. CDM is a mechanism under the Kyoto Protocol, allowing industrialized countries to pay for mitigation projects in developing countries as an alternative to own emissions reductions. This option will end after 2020, however, as the EU then has a *domestic* emission reduction target.[3] There has also been a lot of criticism against CDM credits, especially related to so-called additionality (Carmichael et al., 2016). That is, it is difficult to verify whether or not a CDM project would have taken place in the absence of CDM. Leakage has also been highlighted as a challenge with the CDM (Rosendahl and Strand, 2011).

An alternative option is REDD+ (Reducing Emissions from Deforestation and forest Degradation), which aims at reducing GHG emissions from forests in developing countries. Since deforestation and land use change stand for about 11% of the global carbon emissions (IPCC, 2014), and is far less costly than most other abatement actions (Anger & Sathaye, 2008; Myers, 2007; Nepstad et al., 2007), forest offsetting has been recognized as an important strategy against climate change (Kindermann et al., 2008; van der Werf et al., 2009). Since the 2007 Bali Action Plan, the aim has been to make REDD+ a part of a global climate agreement, where REDD+ credits could be used as offsets in carbon markets (Angelsen, 2014). The idea is that use of financial incentives can change the behavior of forest users, i.e., by paying the forest actors to conserve the forest

[1] Leakage mainly occurs through two channels, i.e., i) fossil fuel markets; and ii) markets for EITE goods. This paper focuses on leakage in the latter case. The theoretical literature on leakage goes back to Markussen (1975), and other important contributions are Hoel (1996) and Copeland (1996).
[2] https://ec.europa.eu/clima/policies/ets/allowances/leakage_en
[3] https://ec.europa.eu/clima/policies/ets/credits_en

(Angelsen et al., 2012). REDD+ credits suffer from many of the same challenges as CDM, however, such as additionality and leakage.

In this paper, we examine the impacts of introducing an offset mechanism into a carbon market, first analytically and then numerically in the context of the EU ETS and REDD+. We consider the effects of discounting offset credits, so that the conversion rate between a REDD+ credit and ETS allowances may be less than one. That is, the regulated firms may need more than one REDD+ credit to offset one unit of domestic emissions. This has been suggested as a response to the additionality problem, but also to avoid full crowding out of domestic emission reductions (Angelsen, 2014).

In the analytical part of the paper, we show that under certain conditions it is globally welfare improving for a single region to introduce an emission offset mechanism for the emission-intensive and trade-exposed sector, when an emission price is already implemented in the region. We also find this to be the case when the offset mechanism is introduced for all the participants in the regional carbon market. Next, we supplement with results from a stylized computable general equilibrium (CGE) model calibrated to data for the world economy. The numerical results support our analytical findings in the context of the EU ETS. That is, the REDD+ offset mechanism is welfare improving, both for the EU and the world, regardless of whether the offset mechanism is introduced for only the trade-exposed sector or for the whole EU ETS. The optimal conversion rate, however, is far below one according to our simulations, as it implies lower global emissions. Global emission reductions are maximized with a conversion rate around 25 percent in our main simulations. Leakage in the international markets are taken into account, both when it comes to EITE products and forest and agricultural products.

There are some studies that have explored the effects of including REDD+ credits in a global carbon market (Angelsen et al., 2014; Anger & Sathaye, 2008; Bosetti et al., 2011; Den Elzen et al., 2009; Dixon et al., 2008; Eliasch, 2008; Murray et al., 2009). They overall suggest an emission price reduction in the range of 22-60%, depending on the scope and rules for REDD+ credit inclusion. Bosello et al. (2015) examines the effect of introducing REDD+ credits in the EU ETS, and finds that reduced deforestation both decreases climate change policy costs and carbon leakage. The study is one of very few that have explored some of the effects of introducing REDD+ in the EU ETS.

Our paper builds on the basic model in Kaushal and Rosendahl (2017), and the basic idea in Bosello et al. (2015) of introducing REDD+ credits offset in the EU ETS. However, whereas the latter paper does not distinguish between trade-exposed and non-trade exposed-sectors, we consider the case where only the emission-intensive and trade-exposed sector can offset their emissions through REDD+ credits. Further, we examine the welfare effects of introducing REDD+ credits in the EU ETS, accounting for the benefits of reduced global emissions as well. As mentioned above, we also consider different conversion rates between

REDD+ credits and EU ETS allowances. Introducing REDD+ credits into the EU ETS would provide large-scale funding for REDD+ programs, and higher global emission reductions can be achieved for a lower mitigation cost if the conversion rate is set below one (Angelsen et al., 2014; Angelsen et al., 2017).

The remainder of this paper is organized as follows. In section 2 we introduce our theoretical model, and analyze the welfare effect of an emission offset mechanism, when an emission trading system is already in place in the policy region. In section 3, we transfer our analysis to a stylized computable general equilibrium model. The model is based on the theoretical model in section 2 and calibrated to data for the world economy. Finally, section 4 concludes.

2. Theoretical model

Consider a theoretical model with 3 regions, $j = \{1,2,3\}$, and four goods x, y, q and z. Good x is emission-free and tradable, y is emission-intensive and tradable (EITE), q is the tradable forest and agricultural good, while z is emission-intensive and non-tradable. The same types of goods produced in different regions, are assumed homogenous in this analysis. Carbon leakage may take place through two channels; i) increased production of the q good from non-REDD+ regions when credits are introduced in REDD+ regions, and ii) relocating production of the y good. The market price for the goods x, y, q and z in region j are denoted p^{xj}, p^{yj}, p^{qj} and p^{zj}.

The representative consumer's utility in region j is given by $u^j(\bar{x}^j, \bar{y}^j, \bar{q}^j, \bar{z}^j)$, where the bar denotes consumption of the four goods. The utility function follows the normal assumptions; twice differentiable, increasing and strictly concave.

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

$$\bar{x}^1 + \bar{x}^2 + \bar{x}^3 = x^1 + x^2 + x^3$$
$$\bar{y}^1 + \bar{y}^2 + \bar{y}^3 = y^1 + y^2 + y^3 \qquad (1)$$

$$\bar{q}^1 + \bar{q}^2 + \bar{q}^3 = q^1 + q^2 + q^3$$
$$\bar{z}^j = z^j$$

2.1. Emission price and carbon offset credit

In the following sections, we will look at two different cases of how the offset mechanism can be introduced into the regional emission trading system. First we assume that the regulating region only allows the emission-intensive and trade-exposed sector to offset their emission with REDD+ credits, which we will refer to as scenario 1. Next, we allow the sector to buy and sell permits to the emission-intensive and non-trade-exposed sector as well, which we will refer to as scenario 2.

We assume that region 1 already regulates emission from production of the y and z goods through a cap-and-trade system. Region 2 is where REDD+ is introduced, while region 3 has no climate regulating policy. In order to reduce the mitigation cost and counteract carbon leakage from region 1 to region 2 and 3, the regulating region has implemented the possibility for the EITE producer good y to offset emission through REDD+ credits. The binding cap on total emission in region 1, $\bar{E}^1$, is then:

$$\bar{E}^1 = e^{y1} - \alpha\left(e_0^{q2} - e^{q2}\right) + e^{z1} \tag{2}$$

where the emission price t^1 balances the emission trading market. e_0^{q2} is the initial emission from producer q in region 2, and it is assumed that $\left(e_0^{q2} - e^{q2}\right) \geq 0$. α determines the conversion rate between emission allowances and offsets, that is, one offset corresponds to α allowances, where $0 < \alpha \leq 1$.[4] Thus, the producer of good y can either buy allowances through the emission market, or buy emission offset through REDD+ credits. The lower is α, the more offsets must be bought to be in compliance. As the z sector is not trade-exposed, we first consider the case where there is no offset considered to producer of this good, and sector y cannot resell permits to sector z. This implies that when offsets are allowed, there will be separate (binding) caps on emissions in the two sectors, $\bar{E}^{y1}$ and $\bar{E}^{z1}$, where $\bar{E}^{z1} = e^{z1}$ and $\bar{E}^{y1} = e^{y1} - \alpha\left(e_0^{q2} - e^{q2}\right)$. Consequently, the emission market is separated for the two sectors but the cap on total regional emission is still fixed. The producer can buy and sell permits within their sector but not across sectors, which necessitates the emission price to be sector specific in region 1, t^{y1} and t^{z1}.

The REDD+ credit market in region 2 consists of the supplier, producer q^2, and demand from producer who want to offset their emission, producer y^1. The suppliers reduce their emissions, as long as they receive a

[4] With α = 1, we have the special case of perfect offset of emission for producer y in region 1 through REDD+ credits.

payment for these services that outweigh their costs.[5] The price of REDD+ credits r, which is the price per unit emission reduction for producer q in region 2, balances the supply and demand of credits.[6] The total cost of reducing emission through REDD+ credits is then for producer y in region 1:

$$r^2\left(e_0^{q2} - e^{q2}\right).$$

This is also the payment that the producer q^2 receives for abatement. Based on the amount of REDD+ credits bought by producer y in region 1, y^1 would need fewer emission permits such that their savings are:

$$\alpha t^1\left(e_0^{q2} - e^{q2}\right).$$

Thus, the competitive producers in region j=1,2,3 maximize profits π^j such that:[7]

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

$$Max_{y^{ij},e^{yj},e^{q2}}\, \pi_j^y = \sum_{i=1}^{3}\left[p^{yi}y^{ij}\right] - c^{yj}\left(y^j, e^{yj}\right) - t^{yj}e^{yj} + \alpha t^{yj}\left(e_0^{q2} - e^{q2}\right) - r^2\left(e_0^{q2} - e^{q2}\right)$$

$$Max_{q^{ij},e^{qj}}\, \pi_j^q = \sum_{i=1}^{3}\left[p^{qi}q^{ij}\right] + r^j\left(e_0^{qj} - e^{qj}\right) - c^{qj}\left(q^j, e^{qj}\right)$$

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

As explained above, we have that $t^{y2} = t^{z2} = t^{y3} = t^{z3} = r^1 = r^3 = 0$. Thus, producer of good y in region 2 and 3 do not buy REDD+ credits r^2. While we will now present the case in scenario 1, it is essential to note that by assuming $t^{y1} = t^{z1} = t^1$, we transform the expressions from scenario 1 to the case in scenario 2.

Assuming interior solution, we derive the first order conditions for producer y:

$$\frac{\partial \pi_1^y}{\partial y^1} = p^{y1} - c_y^{y1} = 0;\quad \frac{\partial \pi_2^y}{\partial y^2} = p^{y2} - c_y^{y2} = 0;\quad \frac{\partial \pi_3^y}{\partial y^3} = p^{y3} - c_y^{y3} = 0$$
$$\frac{\partial \pi_1^y}{\partial e^{y1}} = c_e^{y1} + t^{y1} = 0 \tag{3}$$
$$\frac{\partial \pi_1^y}{\partial e^{q2}} = \alpha t^{y1} - r^2 = 0$$

[5] Services such as forest conservation, sustainable forest management, improving the forest carbon stocks or other projects.
[6] We will later show that r is determined by the marginal abatement cost for producer q^2.
[7] To simplify notation, we replace $\sum_{i=1}^{3} x^{ij}$ with x^j in the equations.

$$\frac{\partial \pi_2^y}{\partial e^{y2}} = \frac{\partial \pi_3^y}{\partial e^{y3}} = c_e^{y2} = c_e^{y3} = 0$$

and the first order conditions for producer q:

$$\frac{\partial \pi_1^q}{\partial q^1} = p^{q1} - c_q^{q1} = 0; \quad \frac{\partial \pi_2^q}{\partial q^2} = p^{q2} - c_q^{q2} = 0; \quad \frac{\partial \pi_3^q}{\partial q^3} = p^{q3} - c_q^{q3} = 0$$

$$\frac{\partial \pi_2^q}{\partial e^{q2}} = c_e^{q2} + r^2 = 0 \tag{4}$$

$$\frac{\partial \pi_1^q}{\partial e^{q1}} = c_e^{q1} = 0; \quad \frac{\partial \pi_3^q}{\partial e^{q3}} = c_e^{q3} = 0$$

From equation (3) and (4), the first line shows that the price for the good is equal to the marginal cost of producing that same good. In the second line in (3), the left-hand side shows that the marginal abatement cost of emission is equal to the emission price in region 1 for producer y. From the third line in (3) and second line in (4) we have that the interior solution requires that the price of REDD+ credits in region 2 is equal to the marginal abatement cost of emission for the producer of good q^2, i.e., $r^2 = -c_e^{q2}$. The last line in (3) and (4) shows that the marginal abatement cost of emission is (as expected) equal to zero for the non-regulated regions and unregulated sectors.

Next, we derive the first order conditions for producer x and z:

$$\frac{\partial \pi_1^x}{\partial x^1} = p^{x1} - c_x^{x1} = 0; \quad \frac{\partial \pi_2^x}{\partial x^2} = p^{x2} - c_x^{x2} = 0; \quad \frac{\partial \pi_3^x}{\partial x^3} = p^{x3} - c_x^{x3} = 0$$

$$\frac{\partial \pi_j^z}{\partial z^j} = p^{zj} - c_z^{zj} = 0$$

$$\frac{\partial \pi_1^z}{\partial e^{z1}} = c_e^{z1} + t^{z1} = 0 \tag{5}$$

$$\frac{\partial \pi_2^z}{\partial e^{z2}} = c_e^{z2} = 0; \quad \frac{\partial \pi_3^z}{\partial e^{z3}} = c_e^{z3} = 0$$

We see that the interior solution requires that the prices of the three tradable goods x, y and q are equalized across regions, as they are homogenous with no cost of trade, i.e., we may define:

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

The representative consumer in region j maximizes utility given consumption prices and an exogenous budget restriction M^j:

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

Differentiating the *Lagrangian* function w.r.t the goods, we get the following first-order conditions:

$$\frac{\partial \mathcal{L}}{\partial \bar{x}^j} = u_{\bar{x}}^j - p^x = 0, \qquad \frac{\partial \mathcal{L}}{\partial \bar{y}^j} = u_{\bar{y}}^j - p^y = 0, \frac{\partial \mathcal{L}}{\partial \bar{q}^j} = u_{\bar{q}}^j - p^q = 0, \qquad \frac{\partial \mathcal{L}}{\partial \bar{z}^j} = u_{\bar{z}}^j - p^{zj} = 0 \tag{6}$$

where we have assumed interior solution, and normalized the utility functions so that $\lambda^j = 1$.

Finally, we assume that the regions have a balance-of-payment constraint. The net export from a region is equal to domestic production minus domestic consumption. Given the assumption of one global price for each of the tradable goods, we have from (3), (4) and (5) that

$$p^y(y^j - \bar{y}^j) + p^x(x^j - \bar{x}^j) + p^q(q^j - \bar{q}^j) = 0 \tag{7}$$

2.2 Change in emission price

In this section, we will show how the change in α affects the emission price t for the producer of good y in scenario 2. However, the results also holds for the emission price t^y in scenario 1. As discussed in the introduction, the assumption is that abatement through REDD+ credits for producer y is less costly than reducing emission on their own. With a single emission market in region 1 and thus one emission price for both sectors, we have established with equation (2) – (5) that the relationship between the emission price t^1, REDD+ credit price r^2, and α is $t^1 = \frac{r^2}{\alpha}$. Both t^1 and r^2 are endogenous, balancing their respective markets, and depend on the marginal abatement cost; c_e^{y1}, c_e^{z1} and c_e^{q2}. The emission price for producer of good y (t^1) will decrease with increasing α. This can be shown by first taking the derivative of (2) and $t^1 = \frac{r^2}{\alpha}$ with respect to α:

$$\frac{\partial \bar{E}^1}{\partial \alpha} = \frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha} + \alpha \frac{\partial e^{q2}}{\partial \alpha} - \left(e_0^{q2} - e^{q2}\right) = 0$$

$$\frac{\partial r^2}{\partial \alpha} = t^1 + \alpha \frac{\partial t^1}{\partial \alpha}$$

To show that t^1 decreases with α, let us first assume the opposite, i.e., $\frac{\partial t^1}{\partial \alpha} \geq 0$. Higher or unchanged emission price implies that the demand for emission permits in the region decreases or stay unchanged, i.e., both e^{y1} and e^{z1} would decrease or remain the same. From the second equation above, we see that $\frac{\partial t^1}{\partial \alpha} \geq 0$ would further imply that r^2 increases with increasing α, i.e., $\frac{\partial r^2}{\partial \alpha} > 0$. This further implies that emission from producer of good q in region 2, e^{q2}, would decrease. With $\left(e_0^{q2} - e^{q2}\right) \geq 0$, we thus have one strictly negative term and the remaining terms non-positive in the expression for $\frac{\partial \bar{E}^1}{\partial \alpha}$ above. As the expression must be equal to zero, this doesn't add up. Therefore, we must have that the emission price t^1 will decrease with increasing share of α. It is straightforward to show that this is also true for t^{y1} in scenario 1. Hence, we have the following result:

Lemma 1. *Let the emission price in region i,* t^i*, the price of emission offset credits in region j,* r^j*, and the conversion rate between offsets and allowances in region i from region j,* α*, be given by equations (2) - (5), i.e.,* $t^i = \frac{r^j}{\alpha}$*. Further, assume that the conversion rate in region i is* $0 < \alpha \leq 1$*. Then, increasing the conversion rate in region i would reduce the emission price in region i.*

Proof. *The lemma follows from equations (2) - (5) as explained above.*

2.3 The global welfare effect

We express the global welfare as:

$$W^G = \sum_{j=1,2,3} \Big[u^j(\bar{x}^j, \bar{y}^j, \bar{q}^j, \bar{z}^j) - c^{xj}(x^j) - c^{yj}(y^j, e^{yj}) - c^{qj}(q^j, e^{qj}) - c^{zj}(z^j, e^{zj}) \\ - \tau^1(e^{yj} + e^{qj} + e^{zj})\Big] \tag{8}$$

where τ^1 is region 1's valuation of reduced global GHG emissions. We will refer to this as the *Pigouvian* tax.[8]

We first consider scenario 1, so that t^{y1} and t^{z1} may differ. By differentiating with respect to α, we arrive at the following result:

Lemma 2. *Let the global welfare be given by equation (8). Then the global welfare effect of increasing the conversion rate* α *for producer of good* y *is given by:*

$$\frac{\partial W^G}{\partial \alpha} = \left(\frac{r^2}{\alpha} - \tau^1\right)\left(e_0^{q2} - e^{q2}\right) - (1-\alpha)\tau^1 \frac{\partial e^{q2}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right) \tag{9}$$

Proof. *See Appendix A.*

[8] The correct definition of the Pigouvian tax is the global marginal external costs of emissions. Whether τ^j reflects this, or only domestic costs of global emissions, does not matter for the analytical results.

Given our assumption of $0 < \alpha \leq 1$ and $\left(e_0^{q2} - e^{q2}\right) > 0$, equation (10) shows that if $\tau^1 = 0$ then $\frac{\partial W^G}{\partial \alpha} > 0$. That is, if we disregard the damage cost of emissions, then the global welfare effect is positive with increasing offset conversion rate. In this case, the positive welfare effect of increasing α is simply a pure global cost saving.

It is of course more reasonable to assume that $\tau^1 > 0$. If the domestic emission price is equal to the *Pigouvian* tax, the first term becomes zero since $t^1 = \frac{r^2}{\alpha}$. As t^1 is reduced when offsets are introduced, we may well have that $\tau^1 > \frac{r^2}{\alpha}$. Hence, it seems likely that:

$$\left(\frac{r^2}{\alpha} - \tau^1\right)\left(e_0^{q2} - e^{q2}\right) \leq 0 \tag{10}$$

From Lemma 1 we know that t^1 decreases with α, and hence we must have $\frac{\partial e^{y1}}{\partial \alpha} > 0$. It is more uncertain what happens with e^{q2} though when α increases. Initially, starting from $\alpha = 0$, it must obviously decrease. When $\alpha > 0$, it is more ambiguous what happens when α is further increased. We see from (2) that $\alpha \frac{\partial e^{q2}}{\partial \alpha} = \left(e_0^{q2} - e^{q2}\right) - \frac{\partial e^{y1}}{\partial \alpha}$. As mentioned, the latter term is negative, while the former is positive (when $\alpha > 0$).

The intuitive explanation is that as α increases from a certain level, fewer credits are needed to offset emission by y^1. Thus, if for instance e^{y1} only increases marginally when α is increased, then we may have $\frac{\partial e^{q2}}{\partial \alpha} > 0$, i.e., both e^{y1} and e^{q2} may increase. Hence, $\frac{\partial e^{q2}}{\partial \alpha}$ is in general ambiguous. As α approaches 1, we see that the size of the second term approaches zero. If $t^1 = \tau^1$, the welfare effect then comes down to the very last bracket of equation (9).

The last bracket consists of the leakage effects, and we must consider what will happen with production and hence emissions in unregulated regions and sectors. Increasing α reduces the production cost for producer y in region 1. This would strengthen their competitiveness level on the world market and further lower the price of the good p^y. Production from region 2 and 3 of good y would now be less profitable. Hence, it is likely that:

$$\frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} < 0 \tag{11}$$

From our previous discussion, increasing the share of α would have an ambiguous effect on the abatement for producer q^2. If $\frac{\partial e^{q2}}{\partial \alpha} < 0$, some of this abatement would likely be through lower production. It then seems reasonable that the price p^q increases somewhat, and hence production of q^1 and q^3 increases slightly as well. This would suggest that $\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} > 0$. If instead $\frac{\partial e^{q2}}{\partial \alpha} > 0$, we will have the opposite situation, i.e., $\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} < 0$. In any case, the second term in (9) and this leakage effect go in different directions with respect to welfare, and the sum of these is ambiguous.

As the price of good y decreases, consumers in all regions will buy more of this relatively cheaper good. The effect on p^q on the other hand is ambiguous, as just explained. Still, it is likely that consumption of the z good decreases in all regions as p^y decreases. Hence:

$$\frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha} \leq 0 \tag{12}$$

To sum up, although the effects on emissions in the q market is ambiguous, it seems quite likely that unregulated emissions will decrease when α increases, in which case the last term in (9) is positive.

Based on the discussion of equation (9), we have the following result:

Proposition 1. *Consider a region i that has an emission trading system, where the producer of emission-intensive and trade-exposed goods, y, can offset their emissions through emission credits from a sector q in region j with a conversion rate α. Assume further that the emission price for producer y is equal to or below the Pigouvian tax. Then it is global welfare improving to increase the conversion rate α if the emission from sector q in region j decreases or is unaffected by this increase.*

Proof. *The proposition follows from equations (7) - (12).*

In Appendix A we show that Proposition 1 also holds in scenario 2, i.e., the producer in region 1 sector y can sell their permits to sector z in the same region

3. Numerical analysis

The stylized theoretical analysis explains some of the outcomes of introducing REDD+ credits in a carbon markets. In order to get a more in-depth insights into the proportion of economic effects and the ambiguous results, we now transfer our analysis to numerical simulations with a stylized computable general equilibrium (CGE) model. Incorporating REDD+ credit allowances in EU ETS is of particular interest, as the abatement cost in this region is relatively high and carbon leakage is of concern. Further, we are interested in both Brazil and Indonesia as regions, since they both have a quite dense rainforest whose deforestation is a major source of CO2 emissions. Particularly Brazil is considered as the supplier of REDD+ credits. By separating these two regions we are able to capture the possible leakage effect (and trade patterns) related to participating in REDD+ (see e.g. Alix-Garcia et al. 2012; Gan & McCarl, 2007; Fortmann et al. 2017; Sun & Sohngen, 2009; Velly et al. 2017). Our main question here is whether it is welfare-improving for the EU, and from a global perspective, to implement such an offset mechanism for the emission-intensive and trade-exposed sector, when the effects on global emission and carbon leakage, as well as trade patterns are taken into account.

3.1 Model summary

The model consists of four regions calibrated according to the European Union/ European Economic Area (EU), Brazil (BRA), Indonesia (IDN) and rest of the world (ROW). The four regions have five production sectors: non-carbon and tradable production x, carbon-intensive and tradable production y, carbon-intensive and non-tradable production z, agriculture and forestry production q (tradable), and fossil energy production f (non-tradable). Consistent with the theoretical analysis, x, y, z and q an only be used in final consumption, while f can only be used in production (of y and z). Hence in line with the theoretical analysis, we focus on the carbon leakage related to the competitive channel for the goods z and q (the latter related to the REDD+ market). We distinguish between domestic and foreign produced goods, with no transportation cost.

Capital, labor, fossil energy, fossil resources and land are the input factors in production. Capital, labor and fossil energy are mobile between sectors but immobile between regions. The fossil resource is only used in fossil energy production, while land is only used in agriculture and forestry production. Both fossil resource and land are immobile between sectors and regions. The producers combine the input factors at minimum cost subject to a technological constraints. Production of x, q, y and z is expressed by two level constant-elasticity-of-substitution (CES) cost functions, describing the substitution possibilities between capital, labor, fossil energy and land use. For f production, the two level CES cost function consists of capital, labor and resource. At the top level, we have the CES function with substitution between energy/resource/land and the value-added (capital and labor) composite. At the second level, the CES value-added composite consists of substitution between capital and labor[9]. Fossil related emission is proportional to the use of fossil energy as input for production, and emission related to land use change is proportional to the use of land in production of good q. Thus, the total emission reduction takes place by reducing energy or land use through either; i) substitution of energy/land by the value-added composite, or ii) reducing the production output.

[9] See appendix B for CGE-summary and nesting in different sectors.

The final consumption in each region is determined by a representative agent's utility, which is maximized subject to a budget constraint. The agent's utility is given as a CES combination of final consumption of domestic and imported goods, and the budget constraint is the monetary value of regional endowment of capital, labor, resource and land.

3.2 Data and calibration

The calibration procedure for the general equilibrium analysis is standard, where base-year data defines some of the exogenous parameter values. 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).

We base the calibration of the model on World Input Output Database (WIOD) data (base-year 2009)[10], and we further reconstruct the empirical data to fit the model from the theoretical analysis. The WIOD-dataset of the world is based on 43 regions with 56 sectors, linked with corresponding data of fossil related CO_2 emission from each sector. We map all the WIOD sectors into five merged sectors x, q, y, z and f.[11] Further, we stick to the same assumption from the theoretical analysis that there are no carbon related emissions in sector x, and thus set emissions in this sector equal to zero[12]. For the agriculture and forestry sector, we combine the data of land use from WIOD with other studies. Carbon sequestration in the different regions related to forest and land use change are collected from Malhi et al. (1999), IPCC (2000), Gan and McCarl (2007), Sun and Sohngen (2009), Kindermann et al. (2008) and FAOSTAT (2018). While we base the values on these studies, it is important to note that the sequestration rate varies and depends on the age and the types of forest. Further, the land prices in the regions are based on data from EUROSTAT (2016), USDA (2018), SEAB (2016), and Dislich et al. (2018). These data where relatively difficult to collect, and ideally an open-access database will be beneficial for similar future studies[13]. Finally, we structure the production function for sector q and calibrate the substitution between land use and value-added composite (capital and labor), and we calibrate the marginal abatement cost estimates according to the collected data.

The net exports in sector x, q and y in the base-year is based on the difference between a region's production and consumption, and the balance of payment constraint is incorporated in the CGE model. The calibrated z sector consists of some sectors with fairly limited trade. Because there is no trade for the z sector in the

[10] The model is implemented as a Mixed Complementarity Problem in GAMS, using the PATH-solver.
[11] See appendix C for mapping of WIOD sectors.
[12] In the WIOD dataset, sector x accounted for 14% of the global (fossil related) CO_2 emissions in 2009.
[13] Coomes et al. (2018):"An open-access, global land price database would enable policymakers, scientists, and civic society to better grapple with the economic, social, and environmental challenges posed by global change."

theoretical analysis, we simply assume that produced quantity in a region is the same as consumed quantity in the same region.

The representative agent is assumed to have a CES utility function, which is calibrated with share parameters of consumption set to base-year shares. We distinguish between domestic and foreign goods by origin, based on Armington's approach (Armington, 1969). At the top level in the CES utility function, we use a substitution elasticity of 0.5 between the four goods x, q, y and z. At the second level, we integrate a substitution between domestic and imported goods x, q and y. Finally at the third level, we differentiate between the origins of the foreign produced goods. At the second level for goods x and y the substitution elasticity is set to 16, and 32 at the third level. For good q the substitution elasticity at the second level is set to 4, and the third level to 8. The size of the substitution elasticities determine how close goods produced with different origins are.[14] Hence, we implicitly assume that the agricultural and forest good q is less trade-exposed than the emission-intensive (manufacturing) good y and the non-carbon good x. However, there are uncertainties related to how trade-exposed the q good is. Particularly, the output response by other regions and carbon leakage that occurs in this sector depends on forest type, product variety, international transport costs, and carbon up take (García et al., 2018). Hence, we will also consider alternative assumptions about the Armington elasticities in the sensitivity analysis.

3.3 Policy scenarios

The latest available WIOD data with corresponding CO_2 emission level for different sectors is from 2009. Even though the EU ETS was already in place, we consider the calibrated equilibrium in 2009 as a business-as-usual scenario[15]. The reference (*REF*) policy scenario is when the EU/EEA imposes an emission reduction target, using an economy-wide ETS with either auctioning or unconditional grandfathering. The reduction target is set to 20 percent.[16] Next we consider the same scenarios as discussed in the theoretical analysis, where producer y can buy REDD+ credits to offset its CO_2 emissions. In the offset scenarios we consider different levels of α, where $1/\alpha$ is the number of REDD credits needed to offset one ton of emissions. α is ranging from 0% to 100%, and from Section 2 we know that the price of REDD+ credits will be equal to α times the emission permit price t in the EU ETS. We consider both scenarios examined in the theoretical analysis, where: *1)* only producer y can offset its emissions through REDD+ credits and *cannot* resell emission allowances to sector z, and *2)* producer y can offset its emissions through REDD+ credits and *can* resell emission allowances to sector

[14] Thus, with an infinite Armington elasticity on the second and third levels, it would be possible to transform it into perfect substitution between locally produced and imported goods.
[15] In 2009 the ETS price was roughly 13 Euro per ton CO_2
[16] We can think of this emission target as an additional emission reduction target of 20 percent relative to the base-year emission. Further, the permit price in this chapter is reported without taking into account the 13 Euro per ton CO_2 in 2009.

z. We consider only Brazil (BRA) as the supplier of REDD+ credits, and further assume that the CO_2 emission level for Brazil producer q in the *REF* scenario is taken as the reference level for offsets. Hence, the cap in the EU ETS is endogenously increased by $\alpha\left(e_{ref}^{qBRA} - e^{qBRA}\right) \geq 0$.

Finally, as the global emissions are different across the policy scenarios, we will assume that the emission permit price in the *REF* scenario reflects EU/EEA's valuation of global emission reductions. Finally to examine the sensitivity of our findings, we also present a number of sensitivity analysis in Section 3.5.

3.4 Results

In this chapter, we examine the effects on some key indicators such as emission, leakage rate, welfare, and permit and REDD+ credit prices. We define the leakage rate as changes in emissions in the unregulated regions and sectors divided by emissions reductions in the abating regions and sectors. This is explained in more detail below. The welfare change measure is the ratio between *BAU* and the different policy scenarios. The welfare is defined by the CES utility function for the representative agent minus the valuation of changes in global emissions.

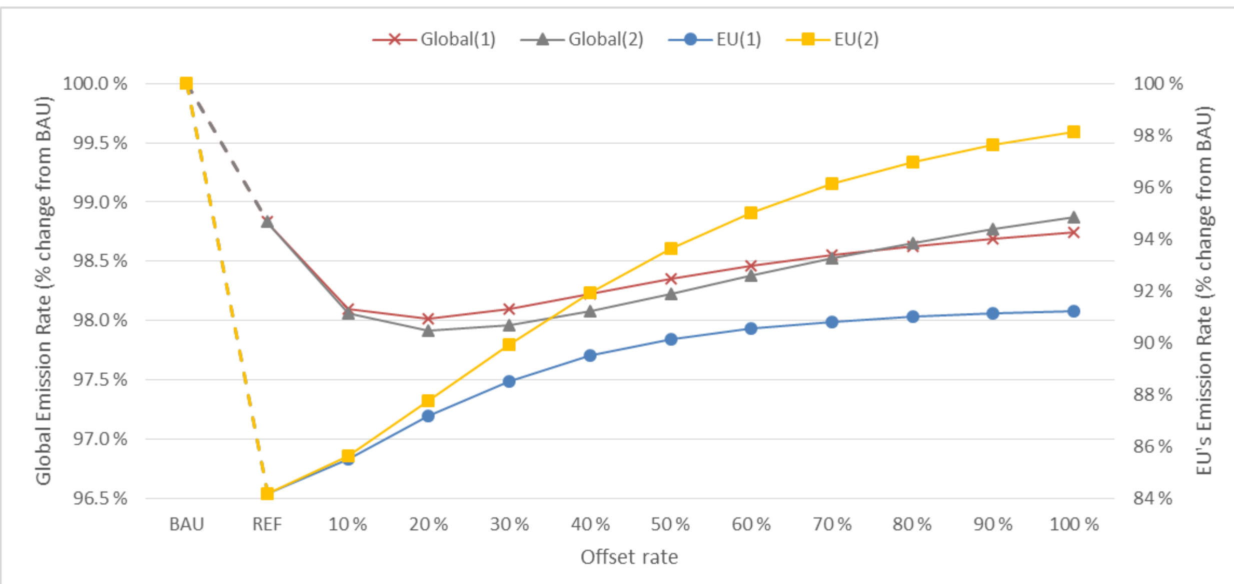

Figure 1: Global and EU's emission rate under different combination of policies in scenario 1 and 2.

Figure 1 shows the effect on the global emission and EU's emission in the different scenarios. The numbers *1* and *2* in the parenthesis behind the legend corresponds to scenario *1* and *2* from our theoretical analysis. Here, we measure the emission rate from both fossil energy and land use change. With only emission pricing in the EU, emissions in the EU declines by 16%, leading to a 1.2% reduction in global emissions. Since sector q is not part of the EU ETS, emission from this sector increases slightly as consumption shifts towards the relatively cheaper goods (x and q). Next, the figure shows that allowing for offsets has a significant impact on global emission, which has a minimum when α is 20%, i.e., one REDD+ credit translates into 0.2 ETS allowances. The global emission rate is a little lower in scenario 2 than in scenario 1, that is, up to an offset rate of 70%. This is due to relatively more offset credits being bought in scenario 2. It follows that EU's emission rate is higher under scenario 2 than scenario 1.

Figures 2 show the effects on leakage in scenario 1 and scenario 2, that is, leakage from regulated sectors in the EU ETS (y and z) to unregulated sectors and regions (both in the EU and other regions). In the *REF* scenario, the unregulated regions and sectors consist of all emissions outside the EU plus emissions from the q sector in the EU. In the offset scenarios, emissions from the q sector in Brazil is no longer treated as unregulated – instead changes in these emissions (vis-à-vis *REF*) are treated as regulated emissions together with the EU ETS emissions (changes in these emissions from *BAU* to *REF* are still treated as unregulated). In the figures, EU_yz shows the leakage rate to energy-intensive producers y and z in other regions, EU_yzq shows the leakage rate from the EU ETS to all other sector (y, z and q), and finally BRA_q, shows the leakage rate from agriculture and forestry producer q in Brazil to sector q in other regions.

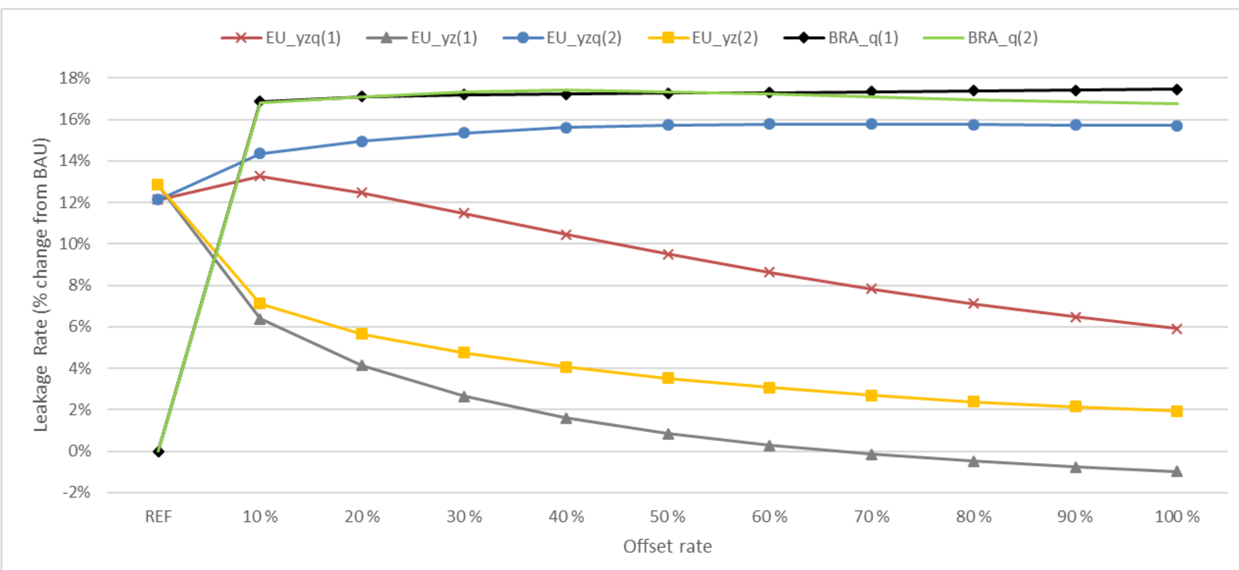

Figure 2: Leakage rate from y, z (and q) in the EU and from q in BRA under different combination of policies in scenario 1 and 2.

In the *REF* scenario, the leakage rate is 13% if we only account for leakage to sector y and z outside the EU. Given no energy trade in our model, (fossil) carbon leakage only happens through the market for EITE-goods. The leakage rate to sector q is however slightly negative, as increased production of good y in the unregulated regions tends to shift the demand for inputs from other production sectors including sector q. Further, by introducing the offset possibilities in the EU ETS, the figure shows that this has a significant impact on the leakage rate to energy-intensive goods (y and z), which becomes negative above 60% offset in scenario 1.

Leakage to sector q actually contributes more to overall leakage in all offset scenarios. It reaches a maximum at 40% offset rate in scenario 1, while increases monotonically with the offset rate in scenario 2. This is due to more demand for offsets in scenario 2, which reduces the production of good q in BRA more than in scenario 1. As a consequence, the producer of good q in the other regions increase their production, and hence emission, even more. Therefore, introducing an offset possibility leads to a bigger reduction in the leakage rate in scenario 1 than scenario 2.

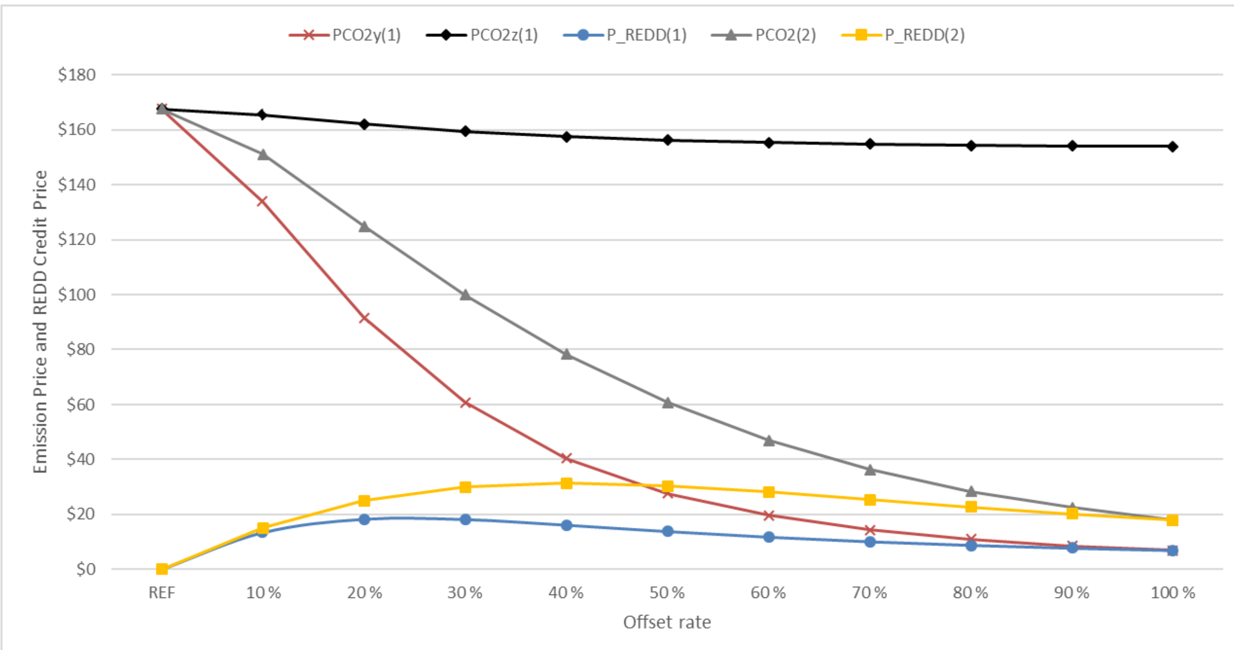

Figure 3: Price of emission and REDD+ credit under different combination of policies in scenario 1 and 2.

As mentioned before, the main reason why leakage from the regulating region decreases is that the REDD+ credits make it less costly to reduce emission. Hence, the offset possibility will tend to decrease the emission price for producers of good y and z in the EU. Figure 3 shows the endogenous emission price for producer y and z, and the REDD+ credit price, in scenario 1. In line with our theoretical analysis, the offset possibility lowers the emission price substantially for the producer of good y. The emission price for the producer of good z decreases to some degree, as consumers now shift their consumption towards the relatively cheaper good y. The same pattern is seen in scenario 2, where producers of good y and z in the EU have one common emission price. Here, too, the emission price decreases rapidly, but less than in scenario 1. Figure 3 show that an increasing offset rate increases the REDD+ credit price initially, as more emission reductions from sector q increase the marginal abatement cost. The REDD+ credit price reaches a top point, however, of around $19 with 25% offset rate in scenario 1, and $32 with 40% offset rate in scenario 2. Recall from our theoretical analysis that the price of REDD+ credits could indeed either increase or decrease with increasing offset rate. On the one hand, a higher offset rate makes REDD+ credits more valuable, leading to higher demand. On the other hand, a higher offset rate also means that fewer REDD+ credits are needed to offset a given amount of emissions. As illustrated by the figures, the former effect is dominating at low offset rates, while the latter is dominating at high rates. Finally, as discussed earlier, demand for REDD+ credits is relatively higher in scenario 2 since both sector y and z benefit from the offset possibilities. As a result, this increases the REDD+ credit price more than in scenario 1.

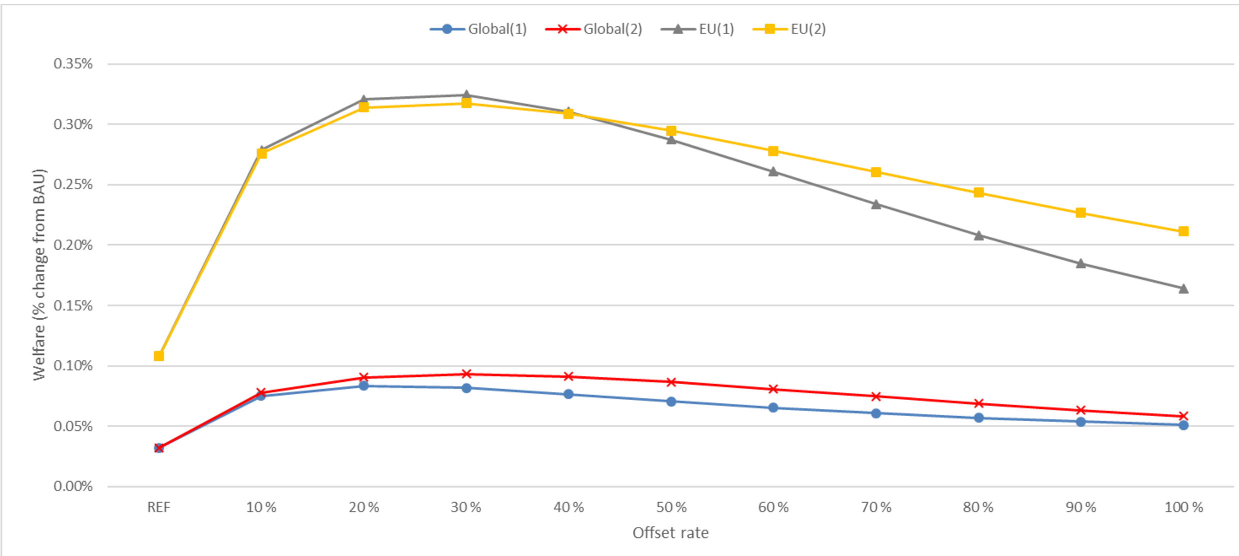

Figure 4: Global and EU's welfare effect under different combination of policies in scenario 1 and 2.

The offset mechanism reallocates production of good y from the unregulating regions back to the EU. Further, global emissions decline with the offset scenario, at least for relatively small offset rates, meaning less climate damages. Figure 4 shows the global welfare change and the welfare change in the EU under the different policies in scenario 1 and 2. The change is shown as a percentage change compared to *BAU*. Here we take into account the change in global emissions, where we use the emission price from *REF* to value these. Note that we credit the effort of emission reduction through REDD+ to the policy region EU. As shown in the figure, emission pricing alone (*REF*) is welfare improving both for the EU and globally. Furthermore, the results suggest an optimal offset rate in the range of 20% in scenario 1 and 25% in scenario 2 for global welfare. These are also the offset rates where global emission is at the lowest, see Figure 1. For the EU, the optimal offset rate is in the range of 25% in both scenarios. If we were to ignore the welfare effects of lower global emissions, the optimal offset rate (both globally and for the EU) increases to 100%. The reason is that the offset possibility is a cost saving policy for the abating region, and hence the welfare gain in the EU (and globally) is highest in scenario 2 when both y and z producers can use offsets. To sum up, from a pure economic perspective, 100% offset rate is optimal as it equalizes marginal abatement costs between the y and z sectors in the EU and the q sector in Brazil, while a lower offset rate is optimal when the benefits of global emission reductions are also accounted for.

3.5 Sensitivity analysis

In the sensitivity analysis, we now examine the effects of changing some of our main assumptions: i) a lower Armington elasticity on traded goods, ii) infinite Armington elasticity (homogenous goods), where domestic and foreign goods are not distinguished by origin anymore, iii) including Indonesia in the REDD+ market, and iv) only 50% additionality of REDD+ credits (i.e., net abatement is only half of what is reported). We only examine scenario 1 in the sensitivity analysis.

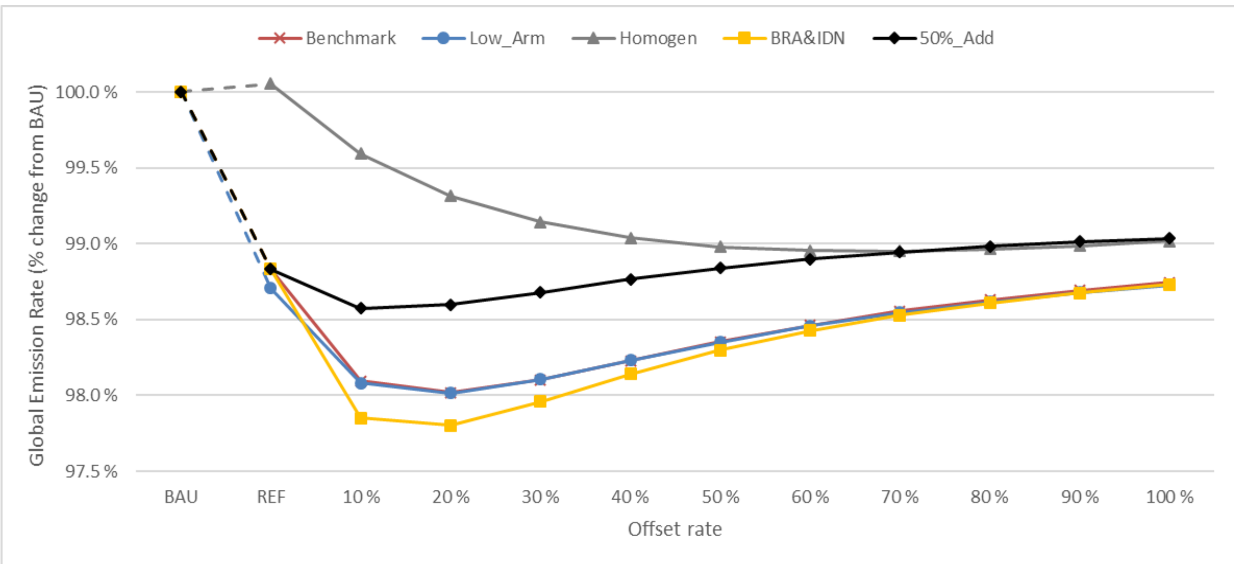

Figure 5: Global emission rate with assumption of lower Armington elasticity (Low_Arm), homogenous goods (Homogen), including Indonesia in the REDD+ market (BRA&IDN), and 50% additionality of REDD+ (50%_Add) under different combination of policies in scenario 1.

With a lower Amington elasticity, we now assume less trade-exposure for producer x, y and q. At the top level in the utility function, we keep the same assumption as before. At the second level for goods x and y the substitution elasticity is set to 4, and 8 at the third level. For good q the substitution elasticity at the second level is set to 2, and the third level to 4. In the case of homogenous goods, we still assume a substitution elasticity of 4 and 8 only for good q, at second and third level respectively. Hence, producer q is still less trade-exposed than producer x and y. In Figure 5 we show how this assumption affects the global emission rate compared to our benchmark assumption in scenario 1. The global emission rate under all the different policy scenarios are lower than the benchmark simulations with higher Armington elasticity. This is mainly a result of less trade-exposure, which limits the leakage more. Further, the numerical simulations still suggest that the offset rate that minimizes global emission is in the range of 20% offset. In the case of homogenous goods, however, more trade exposure (and hence leakage) leads to much lower global emission reductions, and the offset rate that minimizes global emission is much higher (approximately 70%). Moreover, Figure 5 shows that the global emission in fact (slightly) *increases* from *BAU* to the *REF* scenario, and then decreases when REDD+ is introduced.

We show in Figure 6 how the choice of the Armington elasticity affects the global welfare. In general, the lower the Armington elasticity, the higher are the welfare gains under all the different policy scenarios. This is mainly the result of lower global emission, and hence the global benefits of emission reductions being bigger. The optimal offset rate is similar to or slightly higher than the offset rate that minimizes global emissions. With heterogeneous goods, the optimal rate is around 20%, while in the homogenous good case the optimal offset rate is in the range of 90%. The optimal offset rate is slightly higher than the rate that minimizes global emissions as the benefit of lower abatement cost increases with the offset rate (as discussed in section 3.4).

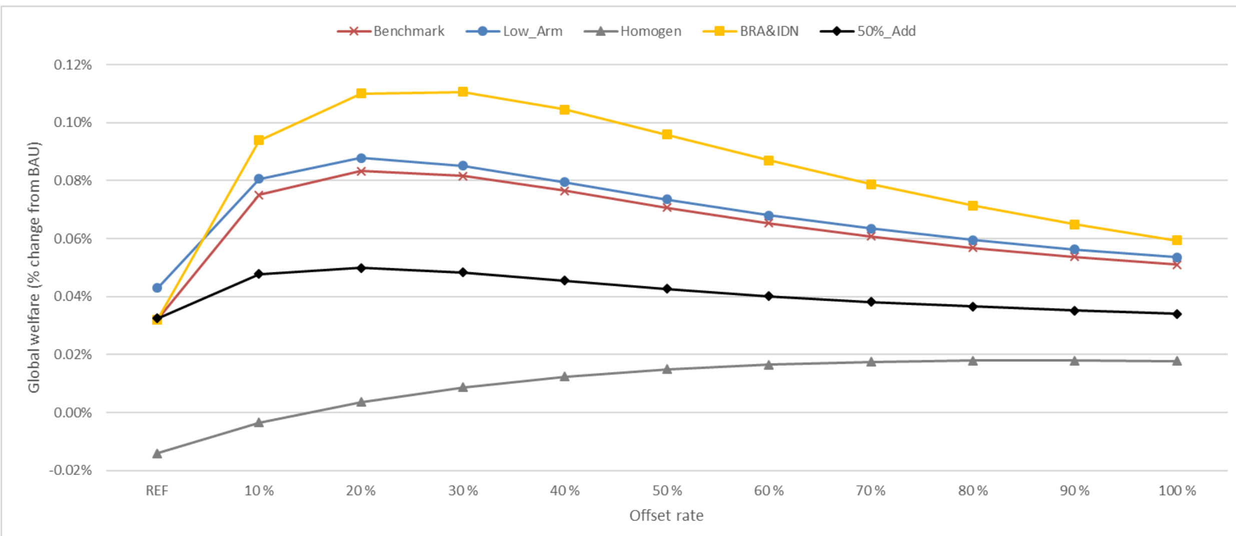

Figure 6: Global welfare effect with assumption of lower Armington elasticity (Low_Arm), homogenous goods (Homogen), including Indonesia in the REDD+ market (BRA&IDN), and 50% additionality of REDD+ (50%_Add) under different combination of policies in scenario 1.

In the benchmark simulations we only consider Brazil as the supplier of REDD+ credits. However, Indonesia is also a country with large rainforests, and among the countries that may participate in a REDD+ initiative. How would an offset mechanism introduced for both Brazil and Indonesia affect global emission and global welfare? In the model, we now replace the reference level of CO_2 emission in Brazil for producer q, with both Brazil and Indonesia, such that $\alpha\left(e_{ref}^{qBRA} + e_{ref}^{qIDN} - e^{qBRA} - e^{qIDN}\right) \geq 0$. Figure 5 shows that global emission is lower than in all the other scenarios considered. The offset rate that minimizes global emission is still in the range of 20%. The lower global emission is due to relatively more offset credits being bought, as the REDD+ credit price is now even lower. That is, with both Brazil and Indonesia supplying REDD+ credits, a similar emission reduction can now be achieved at a lower cost. Figure 6 shows that this has a positive global welfare effect, as the welfare increase is greater than in the benchmark simulations. Also here, Figure 6 suggests that the optimal offset rate is in the range of 20%.

In the last sensitivity analysis, we assume that the net emission reduction in Brazil for producer q is 50% less than reported, that is, the additionality of REDD+ credits is only 50%. All other assumptions are in line with our benchmark simulations. We show in Figure 5 how this could affect the global emission rate. The simulation results suggest that allowing for a conversion rate still has a significant impact on global emission, which now has a minimum in the range of 15%, compared to 20% in our benchmark simulations. The global emission rate remains lower than REF for conversion rates up to 50% in scenario 1 – with higher conversion rates the global emissions are inflated by introducing REDD+ offsets. As for global welfare, Figure 6 suggest an optimal rate in the range of 15% as well. In general, the global welfare is lower than in our benchmark simulations, which is due to the higher global emission.

4. Concluding remarks

Countries that introduce unilateral action to reduce greenhouse gas (GHG) emissions, may face high abatement costs as well as the risk of reduced competitiveness for emission-intensive and trade-exposed (EITE) industries, and corresponding carbon leakage. The economics literature has suggested different approaches to mitigate this type of carbon leakage, and a widely used approach in existing emission trading systems (ETS) is output-based allocation (OBA). In the current paper, we have examined the impacts of instead allowing for Reducing Emissions from Deforestation and Forest Degradation (REDD+) credits to offset domestic GHG emission for the EITE industries. In particular, we have looked into the effects of requiring that the EITE producers may have to acquire more than one offset credit to balance one ETS allowance.

We have shown analytically that under certain conditions it is globally welfare improving for a single region to introduce such an emission offset mechanism for the EITE sector, when an ETS is already implemented in the region. In the welfare calculations, we include the benefits of reduced global emissions. We also find this to be the case when the offset mechanism is introduced for all participants in the domestic carbon market. Next, we have confirmed these results with a stylized computable general equilibrium model calibrated to real world data in the context of the EU ETS and REDD+ credits from Brazil. In particular, the welfare for both the EU and the world as a whole were consistently improved when an offset mechanism was introduced, irrespective of whether the offset mechanism is introduced for only the trade-exposed sector or for the whole EU ETS. The simulations further suggest that it is optimal for the EU to require EITE producers to acquire several REDD+ credits to offset one EU ETS allowance, as this leads to bigger global emission reductions. The numerical simulation also showed that the offset mechanism had a significant impact on the leakage rate to the energy-intensive goods. This was also true for lower conversion rates between REDD+ credits and EU ETS allowances. Further, the leakage rate from agricultural and forestry sector in the REDD+ countries, were positive for all the conversion rates. However, the leakage rate decreased with increasing conversion rate.

Data from different sources were collected to estimate and calibrate the production function's structure, for the agricultural and forestry producer. However, as the literature on carbon uptake, trade exposer and land prices do vary, there could to some extent be uncertainties related to the parameters selection in the numerical simulations. Further, the paper does also not take into account the issues related to implementation, which is a large literature on its own (see e.g. Angelsen et al., 2017; Boer, 2018; Brockhaus et al., 2014; Cadman et al., 2017; Doupe 2015)

As of the Paris climate agreement, the national determined contributions (NDCs) by many tropical rainforest countries, includes a future of REDD+. Particularly, these countries aim to implement REDD+ as part of their contribution to combat climate change. Moreover "positive incentives for activities relating to reducing emissions from deforestation and forest degradation" is also specifically mentioned under article 5 of the agreement (Paris Climate Agreement, 2015). However, none of the potential donor countries have mentioned support for such an emission offset mechanism in their NDCs (Hein et al., 2018). Moreover, the parties are still undecided on the handbook for how Paris climate agreement will measure and interpret a country's emissions and commitments. Further, the rules for international carbon markets and the new sustainable development mechanism, both under Article 6 of the agreement, were pushed to COP25 (Conference of the Parties) 2019 in Chile (Evans & Timperley, 2018). As for now, a report by Streck et al. (2017) does suggest that countries that are parties to the Paris climate agreement could cooperate to implement REDD+ in a carbon market under Article 6, as long as the parties agree on how to deduct from the national emission account of the forest country. It is also worth mentioning that the EU aims to reach its NDC for 2030 through domestic emission reductions. Hence, allowing for REDD+ credits in the EU ETS may be more realistic in a scenario where the EU decides to strengthen its ambitions, which is currently a topic of discussion in the EU.[17]

Böhringer et al. (2017) and Kaushal and Rosendahl (2017) showed that OBA combined with emission pricing may result in regional and global welfare improving effect, when the EITE goods are highly exposed to foreign competition. However, they also find that the opposite might be true when the goods are less exposed. We have shown that a low conversion rate for the emission offset mechanism, combined with emission pricing, could improve the global and regional welfare. Moreover, we find this to be true no matter how trade-exposed the EITE goods are. Thus, we conclude that complementing emission pricing with a certain conversion rate for the emission offset mechanism, seems like a good strategy in terms of regional and global welfare improvement.

[17] https://www.euractiv.com/section/climate-strategy-2050/news/eu-parliament-votes-for-55-emissions-cuts-by-2030/

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Appendix A, Derivations

A1: Global welfare change in scenario 1

By differentiating with respect to α, we arrive have that:

$$\frac{\partial W^G}{\partial \alpha} = \sum_{j=1,2,3} \left[u_x^j \frac{\partial \bar{x}^j}{\partial \alpha} + u_y^j \frac{\partial \bar{y}^j}{\partial \alpha} + u_q^j \frac{\partial \bar{q}^j}{\partial \alpha} + u_z^j \frac{\partial \bar{z}^j}{\partial \alpha} - c_x^{xj} \frac{\partial x^j}{\partial \alpha} - c_y^{yj} \frac{\partial y^j}{\partial \alpha} - c_q^{yj} \frac{\partial q^j}{\partial \alpha} - c_z^{zj} \frac{\partial z^j}{\partial \alpha} \right.$$
$$\left. - \left(\tau^1 + c_e^{yj}\right) \frac{\partial e^{yj}}{\partial \alpha} - \left(\tau^1 + c_e^{qj}\right) \frac{\partial e^{qj}}{\partial \alpha} - \left(\tau^1 + c_e^{zj}\right) \frac{\partial e^{zj}}{\partial \alpha} \right]$$

Since good z is non-tradable, the production in region j is equal to consumption in the same region. Also recall that $c_e^{q1} = c_e^{y2} = c_e^{z2} = c_e^{y3} = c_e^{q3} = c_e^{z3} = 0$:

$$\frac{\partial W^G}{\partial \alpha} = \sum_{j=1,2,3} \left[p^x \left(\frac{\partial \bar{x}^j}{\partial \alpha} - \frac{\partial x^j}{\partial \alpha} \right) + p^y \left(\frac{\partial \bar{y}^j}{\partial \alpha} - \frac{\partial y^j}{\partial \alpha} \right) + p^q \left(\frac{\partial \bar{q}^j}{\partial \alpha} - \frac{\partial q^j}{\partial \alpha} \right) \right] - \left(\tau^1 + c_e^{y1}\right) \frac{\partial e^{y1}}{\partial \alpha}$$
$$- \left(\tau^1 + c_e^{z1}\right) \frac{\partial e^{z1}}{\partial \alpha} - \left(\tau^1 + c_e^{q2}\right) \frac{\partial e^{q2}}{\partial \alpha}$$
$$- \tau^1 \left(\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha} \right)$$

We use our assumptions from (7), differentiate w.r.t α and solve it for p^x:

$$\frac{\partial p^x}{\partial \alpha}(x^j - \bar{x}^j) + p^x \left(\frac{\partial x^j}{\partial \alpha} - \frac{\partial \bar{x}^j}{\partial \alpha} \right) + \frac{\partial p^y}{\partial \alpha}(y^j - \bar{y}^j) + p^y \left(\frac{\partial y^j}{\partial \alpha} - \frac{\partial \bar{y}^j}{\partial \alpha} \right) + \frac{\partial p^q}{\partial \alpha}(q^j - \bar{q}^j) + p^q \left(\frac{\partial q^j}{\partial \alpha} - \frac{\partial \bar{q}^j}{\partial \alpha} \right) = 0$$

Insert this for p^x into our equation:

$$\frac{\partial W^G}{\partial \alpha} = \sum_{j=1,2,3}\left[\frac{\left(\frac{\partial p^x}{\partial \alpha}(x^j-\bar{x}^j)+p^y\left(\frac{\partial y^j}{\partial \alpha}-\frac{\partial \bar{y}^j}{\partial \alpha}\right)+\frac{\partial p^y}{\partial \alpha}(y^j-\bar{y}^j)+\frac{\partial p^q}{\partial \alpha}(q^j-\bar{q}^j)+p^q\left(\frac{\partial q^j}{\partial \alpha}-\frac{\partial \bar{q}^j}{\partial \alpha}\right)\right)}{-\left(\frac{\partial x^j}{\partial \alpha}-\frac{\partial \bar{x}^j}{\partial \alpha}\right)}\left(\frac{\partial \bar{x}^j}{\partial \alpha}\right.\right.$$

$$\left.\left.-\frac{\partial x^j}{\partial \alpha}\right)+p^y\left(\frac{\partial \bar{y}^j}{\partial \alpha}-\frac{\partial y^j}{\partial \alpha}\right)+p^q\left(\frac{\partial \bar{q}^j}{\partial \alpha}-\frac{\partial q^j}{\partial \alpha}\right)\right]-\left(\tau^1+c_e^{y1}\right)\frac{\partial e^{y1}}{\partial \alpha}-(\tau^1+c_e^{z1})\frac{\partial e^{z1}}{\partial \alpha}$$

$$-\left(\tau^1+c_e^{q2}\right)\frac{\partial e^{q2}}{\partial \alpha}-\tau^1\left(\frac{\partial e^{q1}}{\partial \alpha}+\frac{\partial e^{y2}}{\partial \alpha}+\frac{\partial e^{z2}}{\partial \alpha}+\frac{\partial e^{y3}}{\partial \alpha}+\frac{\partial e^{q3}}{\partial \alpha}+\frac{\partial e^{z3}}{\partial \alpha}\right)$$

Can be simplified to:

$$\frac{\partial W^G}{\partial \alpha} = \sum_{j=1,2,3}\left[\frac{\partial p^x}{\partial \alpha}(x^j-\bar{x}^j)+p^y\left(\frac{\partial y^j}{\partial \alpha}-\frac{\partial \bar{y}^j}{\partial \alpha}\right)+\frac{\partial p^y}{\partial \alpha}(y^j-\bar{y}^j)+\frac{\partial p^q}{\partial \alpha}(q^j-\bar{q}^j)+p^q\left(\frac{\partial q^j}{\partial \alpha}-\frac{\partial \bar{q}^j}{\partial \alpha}\right)\right.$$

$$\left.+p^y\left(\frac{\partial \bar{y}^j}{\partial \alpha}-\frac{\partial y^j}{\partial \alpha}\right)+p^q\left(\frac{\partial \bar{q}^j}{\partial \alpha}-\frac{\partial q^j}{\partial \alpha}\right)\right]-\left(\tau^1+c_e^{y1}\right)\frac{\partial e^{y1}}{\partial \alpha}-(\tau^1+c_e^{z1})\frac{\partial e^{z1}}{\partial \alpha}-\left(\tau^1+c_e^{q2}\right)\frac{\partial e^{q2}}{\partial \alpha}$$

$$-\tau^1\left(\frac{\partial e^{q1}}{\partial \alpha}+\frac{\partial e^{y2}}{\partial \alpha}+\frac{\partial e^{z2}}{\partial \alpha}+\frac{\partial e^{y3}}{\partial \alpha}+\frac{\partial e^{q3}}{\partial \alpha}+\frac{\partial e^{z3}}{\partial \alpha}\right)$$

Further:

$$\frac{\partial W^G}{\partial \alpha} = \sum_{j=1,2,3}\left[p^y\left(\frac{\partial y^j}{\partial \alpha}-\frac{\partial \bar{y}^j}{\partial \alpha}+\frac{\partial \bar{y}^j}{\partial \alpha}-\frac{\partial y^j}{\partial \alpha}\right)+p^q\left(\frac{\partial q^j}{\partial \alpha}-\frac{\partial \bar{q}^j}{\partial \alpha}+\frac{\partial \bar{q}^j}{\partial \alpha}-\frac{\partial q^j}{\partial \alpha}\right)+\frac{\partial p^x}{\partial \alpha}(x^j-\bar{x}^j)+\frac{\partial p^y}{\partial \alpha}(y^j-\bar{y}^j)\right.$$

$$\left.+\frac{\partial p^q}{\partial \alpha}(q^j-\bar{q}^j)\right]-\left(\tau^1+c_e^{y1}\right)\frac{\partial e^{y1}}{\partial \alpha}-(\tau^1+c_e^{z1})\frac{\partial e^{z1}}{\partial \alpha}-\left(\tau^1+c_e^{q2}\right)\frac{\partial e^{q2}}{\partial \alpha}$$

$$-\tau^1\left(\frac{\partial e^{q1}}{\partial \alpha}+\frac{\partial e^{y2}}{\partial \alpha}+\frac{\partial e^{z2}}{\partial \alpha}+\frac{\partial e^{y3}}{\partial \alpha}+\frac{\partial e^{q3}}{\partial \alpha}+\frac{\partial e^{z3}}{\partial \alpha}\right)$$

By combining this with equation (1) we have that:

$$\frac{\partial W^G}{\partial \alpha} = -\left(c_e^{y1}+\tau^1\right)\frac{\partial e^{y1}}{\partial \alpha}-(c_e^{z1}+\tau^1)\frac{\partial e^{z1}}{\partial \alpha}-\left(c_e^{q2}+\tau^1\right)\frac{\partial e^{q2}}{\partial \alpha}$$

$$-\tau^1\left(\frac{\partial e^{q1}}{\partial \alpha}+\frac{\partial e^{y2}}{\partial \alpha}+\frac{\partial e^{z2}}{\partial \alpha}+\frac{\partial e^{y3}}{\partial \alpha}+\frac{\partial e^{q3}}{\partial \alpha}+\frac{\partial e^{z3}}{\partial \alpha}\right)$$

$c_e^{y1} = -\frac{r^2}{\alpha}$, $c_e^{q2} = -r^2$ and $c_e^{z1} = -t^{z1}$ from equation (3) - (5) gives us:

$$\frac{\partial W^G}{\partial \alpha} = \left(\frac{r^2}{\alpha} - \tau^1\right)\frac{\partial e^{y1}}{\partial \alpha} + (r^2 - \tau^1)\frac{\partial e^{q2}}{\partial \alpha} + (t^{z1} - \tau^1)\frac{\partial e^{z1}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right)$$

With sector separated emission markets, emission from sector z in region 1 is fixed. Thus, $\frac{\partial e^{z1}}{\partial \alpha} = 0$:

$$\frac{\partial W^G}{\partial \alpha} = \frac{r^2}{\alpha}\frac{\partial e^{y1}}{\partial \alpha} + r^2\frac{\partial e^{q2}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right)$$

By differentiating the emission from sector y in region 1 and set it equal to zero, we have that:

$$\frac{\partial \bar{E}^{y1}}{\partial \alpha} = \frac{\partial e^{y1}}{\partial \alpha} - e_0^{q2} + e^{q2} + \alpha\frac{\partial e^{q2}}{\partial \alpha} = 0$$

$$\frac{\partial e^{y1}}{\partial \alpha} = \left(e_0^{q2} - e^{q2}\right) - \alpha\frac{\partial e^{q2}}{\partial \alpha}$$

Thus, (9) can be expressed as:

$$\frac{\partial W^G}{\partial \alpha} = \frac{r^2}{\alpha}\left(e_0^{q2} - e^{q2}\right) - \tau^1\left(\left(e_0^{q2} - e^{q2}\right) - \alpha\frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right)$$

Further:

$$\frac{\partial W^G}{\partial \alpha} = \left(\frac{r^2}{\alpha} - \tau^1\right)\left(e_0^{q2} - e^{q2}\right) - \tau^1\left((1-\alpha)\frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right)$$

And we finally arrive at (9):

$$\frac{\partial W^G}{\partial \alpha} = \left(\frac{r^2}{\alpha} - \tau^1\right)\left(e_0^{q2} - e^{q2}\right) - (1-\alpha)\tau^1\frac{\partial e^{q2}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right) \qquad (9)$$

A2: Global welfare change in scenario 2

A single emission price t^1 balances the region emission market. Since $t^1 = \frac{r^2}{\alpha}$, then we get (14):

$$\frac{\partial W^G}{\partial \alpha} = \frac{r^2}{\alpha}\left(\frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha}\right) + r^2\frac{\partial e^{q2}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right) \qquad (14)$$

With the assumption of regional emission, we differentiate with respect to α:

$$\frac{\partial \bar{E}^{y1}}{\partial \alpha} = \frac{\partial e^{y1}}{\partial \alpha} - e_0^{q2} + e^{q2} + \alpha \frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha} = 0$$

$$\frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha} = \left(e_0^{q2} - e^{q2}\right) - \alpha \frac{\partial e^{q2}}{\partial \alpha}$$

Further, by simplifying with the same assumption as previously we arrive at equation (9) again:

$$\frac{\partial W^G}{\partial \alpha} = \left(\frac{r^2}{\alpha} - \tau^1\right)\left(e_0^{q2} - e^{q2}\right) - (1-\alpha)\tau^1 \frac{\partial e^{q2}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right)$$

Appendix B: Summary of the numerical CGE model

Indices and sets:

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

Variables:

S^{gr}	Production of good g in r
S_{FE}^{r}	Production of 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
$CO2^{qr}$	Land use related CO_2 emission in region r
p^{gr}	Price of g in r
p_{FE}^{r}	Price of Primary fossil FE in r
p_{KL}^{gr}	Price of value added for g in r
p_{KLF}^{r}	Price of value added for FE in r

p_L^r	Price of labor (wage rate) in r
p_K^r	Price of capital (rental rate) in r
p_O^r	Rent for primary energy resource in r
p_A^{gr}	Price of Armington aggregate of g in r
p_{IM}^{gr}	Price of aggregate imports of g in r
p_{CO2}^{gr}	Price of CO2 emission in r
p_{REDD}^{gr}	Price of REDD credits in r
p_W^r	Price of consumption composite in r
LA^{gr}	Land use endowment in sector g in region r

Parameters:

α^r	Offset share allowance in region r through REDD credits from BRA
σ_{KLE}^{gr}	Substitution between value-added and energy/land 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_O^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

p_{LA}^r	Price of land (rental rate) 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
O_{0}^{r}	Resource endowment of primary fossil energy in region r
$CO2_{MAX}^{r}$	Fossil related CO_2 emission allowance in region r
$CO2_{0}^{gr}$	Land use related CO_2 emission for good g in region r
γ_{CO2}^{r}	Coefficient for land use CO_2 emission 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 fossil primary energy:

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

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

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

Production of fossil primary energy:

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

Sector specific value-added aggregate for FE:

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

Armington aggregate except for FE:

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

Import Composite except for FE:

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

Consumption composite:

$$\pi_W^r = \left(\theta_W^{qr} p_A^{qr(1-\sigma_W^r)} + \theta_W^{xr} p_A^{xr(1-\sigma_W^r)} + \theta_W^{yr} p_A^{yr(1-\sigma_W^r)} + \theta_W^{zr} p_A^{zr(1-\sigma_W^r)} \right)^{\left(\frac{1}{1-\sigma_W^r}\right)} \geq p_W^r \qquad \perp W^r$$

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:

$$O_0^r \geq S_{FE}^r \frac{\partial \pi_{FE}^r}{\partial p_O^r} \qquad \perp {p_O}^r$$

Land use resource:

$$LA^{gr} \geq S^{gr} \frac{\partial \pi_S^{gr}}{\partial P^{gr}} \qquad \perp {p_{LA}}^r$$

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:

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

Allowed CO_2 emission in region, with offset from region BRA:

$$CO2_{MAX}^{r} \geq \kappa_{CO2}^{r} S_{FE}^{r} - \alpha^{r} \left(CO2_{0}^{qBRA} - CO2^{qBRA}\right) \qquad \perp p_{CO2}^{r}$$

Land use related CO_2 emission in region by q:

$$CO2^{qr} \geq \gamma_{CO2}^{r} LA^{qr} \qquad \perp CO2^{qr}$$

Fossil fuel related CO_2 emission in region by g:

$$CO2^{qr} \geq \kappa_{CO2}^{r} S_{FE}^{r} \qquad \perp CO2^{gr}$$

CO_2 emission offset through REDD credits in region:

$$\alpha^{r} p_{CO2}^{r} \geq p_{REDD}^{BRA} \qquad \perp p_{REDD}^{BRA}$$

Consumption by consumers

$$p_W^r W^r \geq p_L^r \left(\sum_g L_0^{gr} + L_{0,FE}^r \right) + p_K^r \left(\sum_g K_0^{gr} + K_{0,FE}^r \right) + p_O{}^r O_0^r + P_{LA}^r LA^{qr} + p_{CO2}^r CO2_{MAX}^r - p_{REDD}^{BRA} \left(CO2_0^{qBRA} - CO2^{qBRA} \right) \quad \perp p_W^r$$

Elasticities: $\sigma_{KLE}^x, \sigma_{KLE}^y, \sigma_{KLE}^z = 0.5$ $\quad \sigma_{KL} = 1$

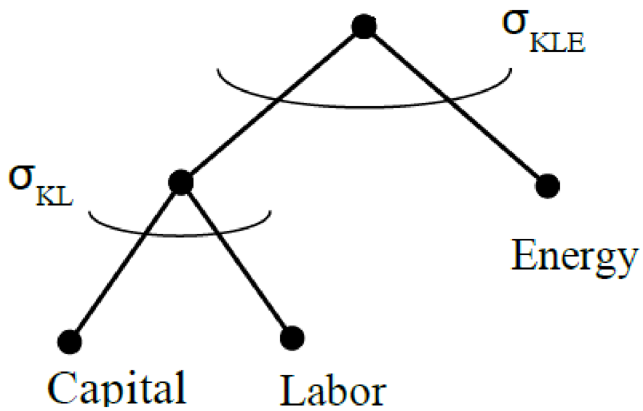

Figure B1: Nesting in production of x, y and z

Elasticities: $\sigma_{KLE}^q = 0.1$ $\quad \sigma_{KL} = 1$

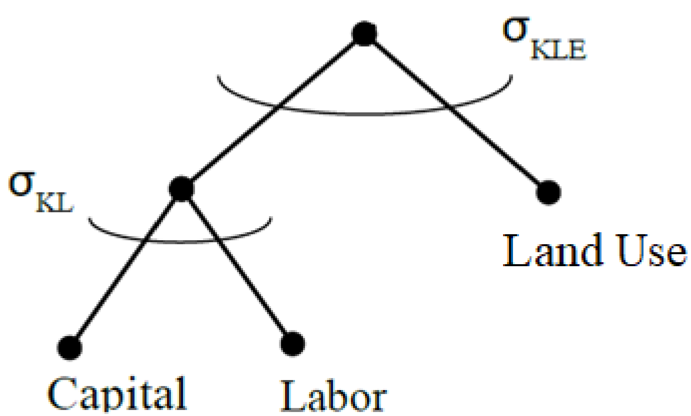

Figure B2: Nesting in production of agriculture and forestry good

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

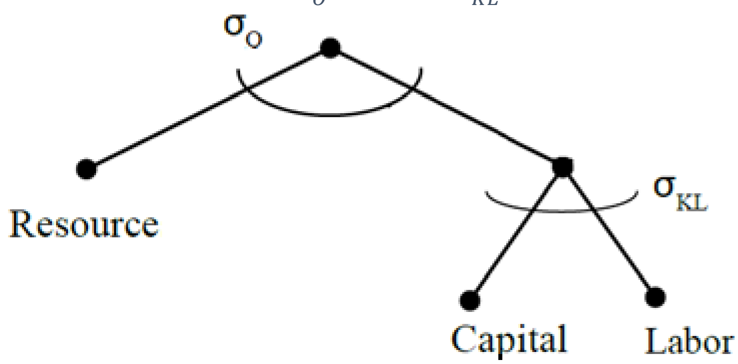

Figure B3: Nesting in production of fossil fuel energy

Elasticity: $\sigma_W = 0.5$

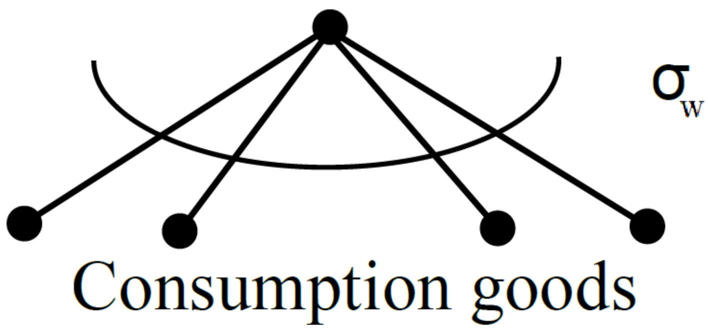

Figure B4: Nesting in final consumption

Appendix C: Mapping of WIOD sectors

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
q: agricultural and forestry goods	Crop and Animal production; Forestry and Logging
x: emission-free and tradable goods	All remaining goods and services

Table C1: Mapping of WIOD sectors to model sectors

Table C1 shows the mapping of the 56 WIOD sectors to three composite sectors in our model.