Norwegian University of Life Sciences
School of Economics and Business

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Kevin R. Kaushal and Knut Einar Rosendahl

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Abstract:

Unilateral actions to reduce CO_2 emissions could lead to carbon leakage such as relocation of emission-intensive and trade-exposed industries (EITE). To mitigate such leakage, countries often supplement an emissions trading system (ETS) with free allocation of allowances to exposed industries, e.g. in the form of output-based allocation (OBA). This paper examines the welfare effects of supplementing OBA with a consumption tax on EITE goods. In particular, we investigate the case when only a subset of countries involved in a joint ETS introduces such a tax. The analytical results suggest that the consumption tax would have unambiguously global welfare improving effects, and under certain conditions have welfare improving effects for the tax introducing country as well. Numerical simulations in the context of the EU ETS support the analytical findings, including that the consumption tax is welfare improving for the single country that implements the tax.

Key words: Carbon leakage; Output-based allocation; Consumption tax

JEL classification: D61, F18, H23, Q54

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1. Introduction

In the Paris climate agreement from 2015, almost all countries in the world committed to reduce emissions of greenhouse gases (GHGs). The countries' nationally determined contributions (NDCs) vary substantially, however, both when it comes to ambitions and indicated measures. Moreover, the NDCs are not legally binding, and it remains to be seen to what degree they will be followed up. Further, the second biggest emitter, the United States, has already signaled withdrawal from the Paris agreement. Thus, it is fair to conclude that the world will still rely on unilateral initiatives to reduce GHG emissions. Unilateral action however leads to carbon leakage, such as relocation of emission-intensive and trade-exposed industries (EITE). The affected industries claim that unilateral emission constraints would raise their production costs, and hence reduces their competitiveness in the world market. This induces more production and emissions in unregulated regions. As a result, the policymaker achieves lower emission level locally, but she risks losing job and industry to other regions, as well as higher GHG emissions abroad.[1]

Although the economic literature suggests that overall carbon leakage is moderate (typically in the range of 5-30%, cf. Zhang, 2012, and Böhringer et al., 2012a – somewhat higher for the EITE industry),[2] it is an important issue in the public debate and in policy decisions. Hence, policymakers have typically either exempted EITE industries from their climate regulation or implemented anti-leakage measures. For instance, sectors that are regulated by the EU Emission Trading System (EU ETS) and "exposed to a significant risk of carbon leakage",[3] are given a large number of free allowances. The allocation is based on product-specific benchmarks to maintain incentives to reduce emissions per unit of output. In order to reduce leakage exposure and limit surplus allowance, the allocation is linked to requirements such as activity level and production volumes (Neuhoff et al. 2016b). Free allowance allocation conditional on output is often referred to as output-based allocation (OBA) (Böhringer and Lange, 2005). A big share of industry sectors in the EU ETS are qualified as significantly exposed to leakage. Similar allocation rules can be found in other carbon markets such as in New Zealand and California, and in the world's biggest carbon market in China which is scheduled to be launched in late 2017(World Bank, 2014; Xiong et al., 2017).

While a large amount of free allowances could mitigate carbon leakage, this implicit output subsidy ends up stimulating domestic production and thereby resulting in too much use of these products globally. The incentives to substitute from carbon-intensive to carbon-free products are weakened. As there is uncertainty about leakage exposure for individual sectors, policymakers may be persuaded to allocate too many permits to

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[1] Cf. also the pollution haven literature, e.g. (Taylor 2005).

[2] 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 leakage rates for the EITE industries specifically are usually found to be somewhat higher than the overall leakage rates, see e.g. Fischer and Fox (2012). The theoretical literature on leakage goes back to Markussen (1975), and other important contributions are Hoel (1996) and Copeland (1996).

[3] https://ec.europa.eu/clima/policies/ets/allowances/leakage_en

too many industries. Sato et al. (2015) finds for instance in the EU ETS that "vulnerable sectors account for small shares of emission", and Martin et al. (2014) concludes for the same market that the current allocation substantially overcompensates for a given carbon leakage risk. Another possible second-best policy instrument for anti-leakage is Border Carbon Adjustments (BCAs), with put charges on embedded carbon imports and refunds on export of EITE goods. Studies have shown that carbon leakage mitigation with BCAs would outperform OBA (Monjon and Quirion, 2011; Böhringer et al. 2014; Fischer & Fox 2012). BCAs may however not be politically feasible, and experts do not agree on whether or not it is compatible with WTO rules (Ismer and Haussner, 2016; Horn and Mavroidis, 2011; Tamiotti, 2011).

Recently a third approach, combining OBA with a consumption tax, 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 impose a consumption tax on top of the same EITE goods. They also show that a certain combination of OBR and a consumption tax would be equivalent to BCA. Further, whereas BCA may be politically contentious to introduce under current WTO rules, a consumption tax does not face the same challenge as it treats domestic and foreign goods symmetrically (Neuhoff et al., 2016a).[4] There are other papers as well that examine a consumption tax related to environmental regulations, both alone or combined with other instruments (Roth et al. 2016; Eichner & Pethig 2015; Holland 2012). Moreover, policymakers in for example California, China, Japan, and Korea are currently operating with a price on carbon that also regulates the embodied carbon from consumption of carbon-intensive products, especially electricity (Munnings et al. 2016;).[5]

Our paper builds on the basic model and findings in Böhringer et al. (2017). However, whereas the latter paper considers one regulating and one unregulating region, this paper examines the case where there is one unregulating region but two regulating regions that have a joint emission trading system with OBA to the EITE-goods. Further, only one of the two regions is considering to impose a consumption tax. The motivation for this is the current situation in Europe, where the EU/EEA countries have set quite ambitious climate targets for 2030 and especially 2050, and where EU institutions have responded enthusiastically to the Paris Climate Agreement outcome (Andresen et al., 2016). At the same time, there is significant political tension and different interests among the member states in the EU when it comes to climate policies. A prime example is the group of European countries depended on domestically produced coal, that have been critical towards EU's long-term climate goals. Other countries, especially in the north and west of Europe, are in favor of increasing the ambitions in line with the Paris agreement's requirement of gradually more

[4] Ismer and Haussner (2016) discuss the correct legal basis under EU law: "inclusion of consumption may be based on Article 192.1 of the Treaty on the Functioning of the EU and thus be adopted without unanimity voting in the Council of the EU."

[5] The extra administrative costs of a consumption tax are probably limited once an OBA scheme is already in place. Neuhoff et al. (2016b) looks at 4047 commodity groups and finds that a consumption tax combined with ETS will have some administrative burdens, but could be moderate if designed correctly. Further, they conclude that "administrative efforts for 77 to 83% of imports could be avoided while still 85% to 90% of import-related carbon liabilities are included".

ambitious targets. In the absence of cooperation to strengthen the climate policies, such as tightening the ETS further, the question is if unilateral action by a single country (or a group of countries) in the EU/EEA such as implementing a consumption tax on EITE goods would be welfare-improving or not.

We show analytically that under certain conditions it is welfare improving for a single region to introduce a consumption tax when the OBA is already implemented jointly in the two abating regions. We also find that the consumption tax has an unambiguously global welfare improving effect. Based on the analytical findings, we complement with results from a stylized numerical simulation model calibrated to data for the world economy, with three regions and three goods. As already indicated, we are particularly interested in the European context and the EU ETS, where a variant of output-based allocation is already in place for emission-intensive goods. The numerical results support our analytical findings, irrespective of which EU/EEA country we consider as the single region imposing a consumption tax. That is, the policy is welfare improving, both for the single country and globally.

As mentioned, the analytical model in our paper builds on the model framework in Böhringer et al. (2017). However, there are several differences between the two papers. First, we examine the case with three instead of two regions. Second, we consider a broader range of policies. While Böhringer et al. consider a carbon tax in their analytical part, and a fixed global emission reduction in the numerical part, we consider the case where two of the three countries are involved in a joint emission trading system and one the two considers imposing a consumption tax. Further, our paper focuses on specific regions, including two regulating regions in Europe, whereas Böhringer et al. divide the world into two equally sized economies. A common assumption in the two papers is that producers can reduce emissions independently of output reductions. This is an important assumption, as the purpose of the policymaker typically is to reduce emissions in EITE industries without reducing the production of the same good. The latter assumption differs from other papers such as Eichner and Pethig (2015). They show that combining production and consumption-based taxes outperform only production-based taxation, but assumes a one to-one relationship between emissions and production of the emission-intensive good.

In section 2 we introduce our theoretical model, and analyze the welfare effect of a consumption tax, when a joint emission trading system combined with OBA is already in place for a subset of regions. In section 3, we transfer our analysis to a stylized multi-region multi-sector numerical model. The numerical 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

We build on the model framework in Böhringer et al. (2017), but extend it to one more region and examine a broader range of policies. Consider a model with 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) goods such as metal and other minerals), while z is emission-intensive and non-tradable (e.g. electricity and transport). Same types of goods, produced in different regions, are assumed homogenous. Carbon leakage may take place through relocating production of the y good, and thus OBA is considered for this sector. The market price for the goods x, y, and z in region j are denoted p^{xj}, p^{yj} and p^{zj}.

The utility for the representative consumer in region j is given by $u^j(\bar{x}^j, \bar{y}^j, \bar{z}^j)$, where the bar denotes consumption of the three goods. The utility function follows the normal assumptions; twice differentiable, increasing and strictly concave, i.e., the Hessian matrix is negative definite and we have a local maximum.

Production of good y in region j is $y^j = y^{1j} + y^{2j} + y^{3j}$, where y^{ij} denotes produced goods in region j and sold in region i (and similarly for the x good). The cost of producing the 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} denote emission from good y 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 and z is decreasing in emissions, 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, $c_e^{yj}, c_e^{zj} \leq 0$ 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:

$$
\begin{aligned}
\bar{x}^1 + \bar{x}^2 + \bar{x}^3 &= x^1 + x^2 + x^3 \\
\bar{y}^1 + \bar{y}^2 + \bar{y}^3 &= y^1 + y^2 + y^3 \\
\bar{z}^j &= z^j
\end{aligned}
\tag{1}
$$

2.1. Climate policies

We assume that regions 1 and 2 have already implemented a cap-and-trade system, regulating emissions from production of the goods y and z in the two regions:

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

where $\bar{E}$ is the binding cap on total emission. The emission trading market is balanced through the emission price t. We further assume that the two regions have implemented output-based allocation (OBA) to producers of the EITE good y, in order to mitigate carbon leakage to region 3, where we assume there is no climate policy imposed. OBA means that producers of good y receive free allowances in proportion to their output, which is an implicit subsidy s to production of good y in regions 1 and 2. The subsidy is proportional to the (endogenous) emission price t and the number of allowances received per unit produced. In the special case where the total number of free allowances to producers of the y good equals the total emissions from this sector, we have that $s = t(e^{y1} + e^{y2})/(y^1 + y^2)$. As the good z is not trade-exposed, there is no OBA to producers of this good.

Next, we assume that region 1 considers to implement a consumption tax v^1 on consumption of the y good, $\bar{y}^1$. The motivation for this tax is, as explained in the introduction, to counteract the negative impacts of OBA, which stimulates too much use of the y good.

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

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

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

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

Since region 3 does not undertake any environmental policy, $t^3 = s^3 = 0$, whereas we have $t^1 = t^2 = t$ and $s^1 = s^2 = s$ (see above). The first order conditions are straightforward to derive, and give the following relationships (assuming interior solution):

$$\begin{gathered} p^{x1} = p^{x2} = p^{x3} = c_x^{x1} = c_x^{x2} = c_x^{x3} \\ p^{y1} + s = p^{y2} + s = p^{y3} + s = c_y^{y1} = c_y^{y2} \\ p^{y3} = c_y^{y3} \\ p^{zj} = c_z^{zj} \\ c_e^{y1} = c_e^{z1} = c_e^{y2} = c_e^{z2} = -t;\, c_e^{y3} = c_e^{z3} = 0 \end{gathered} \tag{2}$$

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

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

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

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

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

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

$$\frac{\partial\mathcal{L}}{\partial\bar{x}^j} = u^j_{\bar{x}} - p^x = 0,\ \frac{\partial\mathcal{L}}{\partial\bar{y}^j} = u^j_{\bar{y}} - (p^y + v^j) = 0,\ \frac{\partial\mathcal{L}}{\partial\bar{z}^j} = u^j_{\bar{z}} - p^{zj} = 0 \tag{3}$$

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

Further, 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 (2) that

$$p^y(y^j - \bar{y}^j) + p^x(x^j - \bar{x}^j) = 0 \tag{4}$$

2.2. The optimal consumption tax in region 1 under OBA

2.2.1. Welfare maximization in region 1

In order to evaluate the different climate policies, we need to specify the regional welfare functions. The welfare in region j can be expressed as:

$$W^j = u^j(\bar{x}^j, \bar{y}^j, \bar{z}^j) - c^{xj}(x^j) - c^{yj}(y^j, e^{yj}) - c^{zj}(z^j, e^{zj}) - \tau^j(e^{y1} + e^{y2} + e^{y3} + e^{z1} + e^{z2} + e^{z3}) \tag{5}$$

where τ^j is region j's valuation of reduced global GHG emissions. We will refer to this as the *Pigouvian* tax.[7] The welfare consists of three elements: i) utility of consumption, ii) costs of production, and iii) costs of emissions. Note that the permit price t might vary from the Pigouvian tax.

[7] 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.

Next, we want to derive the optimal consumption tax v^1 of good y in region 1, given that an emission trading system with OBA for sector y has already been implemented for regions 1 and 2.

By differentiating (5) with respect to v^1, subject to (4), we arrive at the following result for the optimal level of consumption tax v^{1*} in region 1:[8]

$$v^{1*} = \underbrace{\left(\frac{\partial \bar{y}^1}{\partial v^1}\right)^{-1}}_{a} \left[\underbrace{s\frac{\partial y^1}{\partial v^1}}_{b} \underbrace{- \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) - \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1)}_{c} + (-t)\underbrace{\left(\frac{\partial e^{y1}}{\partial y^1}\frac{\partial y^1}{\partial v^1} + \frac{\partial e^{z1}}{\partial z^1}\frac{\partial z^1}{\partial v^1}\right)}_{d} + \tau^1 \underbrace{\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v^1}\right)}_{e} \right] \quad (6)$$

The first term (*a*) is negative since an increase in consumption tax will lead to a decrease in consumption of good y in region 1. Thus, negative (positive) terms inside the bracket tends to increase (decrease) the optimal consumption tax.

An imposed consumption tax in region 1 leads to less total demand of y, and thus the global market price falls. Hence, the production of y decreases in all the three regions and the second term (*b*) in the equation is negative. The term reflects the distortive side effects of the implicit OBA subsidy that causes too much consumption of this good.

Since the consumption of y falls, p^y decreases, i.e., $\frac{\partial p^y}{\partial v^1} < 0$. The consumer will now buy more of the relatively cheaper good x, and hence $\frac{\partial p^x}{\partial v^1} > 0$. Whether part (*c*) is negative or positive will then depend on $(y^1 - \bar{y}^1)$ and $(x^1 - \bar{x}^1)$, i.e., whether region 1 is a net exporter or importer of the two goods. For instance, if region 1 is a net exporter of good x and net importer of good y, the term becomes negative. This term therefore captures the terms-of-trade effects for the region.

The fourth part (*d*) consists of two terms, where the first term inside the parenthesis is negative as explained above. The second term is likely positive, due to interactions in the quota market. Remember that the sum of emissions from sector y and z in regions 1 and 2 must be unchanged and equal to the emission cap. Thus, emissions from production of the good z must increase as long as emissions from producing good y in regions 1 and 2 decline, and this is realized due to a lower quota price when production (and hence emissions) of y decreases. Whether joint emissions from sector y and z in region 1 increases or decreases is thus ambiguous. However, if the consumption tax in region 1 affects producers of good y in region 1 stronger (weaker) than producers in region 2, the sign of part (*d*) is likely positive (negative). Finally, we notice that the higher (lower) the permit price, the more (less) important this part becomes compared to the next part (*e*).

[8] See Appendix A1.

The last part (*e*) captures the emission effect in region 3. When global demand and the market price of good y drop, emissions related to producing this good in region 3 also decrease, $\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} < 0$. The effects on consumption of the non-tradable good z, and hence production and emissions, in region 3 are ambiguous. However, it seems very likely that the sum of the two terms in part (*e*) is negative, i.e., that emissions in region 3 decline when the consumption tax is imposed on good *y* in region 1:

$$\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v^1}\right) < 0 \tag{7}$$

Recall that the first term (*a*) is negative. Then there are two negative and two ambiguous terms inside the bracket. Hence, the sign of the optimal consumption tax is in general ambiguous. However, if region 1 is not a net exporter of the y good, and if producers in regions 1 and 2 react symmetrically to the consumption tax (i.e., for the y good and the z good), then the optimal consumption tax in region 1 is unambiguously positive. Hence, we have the following proposition:

Proposition 1. Consider a region i that has a joint emission trading system with another region j, where output-based allocation is implemented for production of EITE-goods. Then it is optimal for region i to also impose a consumption tax on EITE-goods if it is not a net exporter of EITE-goods *and* producers in regions i and j react symmetrically to the consumption tax.
Proof: The proposition follows from the discussion of equation (6)

If the consumption tax is imposed in both region 1 and region 2 ($v^1 = v^2 = v$), and we consider the joint welfare in these two regions (assuming a common valuation of global emission reduction equal to τ), the optimal consumption tax becomes:

$$v^* = \left(\frac{\partial(\bar{y}^1+\bar{y}^2)}{\partial v}\right)^{-1}\left[s\frac{\partial(y^1+y^2)}{\partial v} + \frac{\partial p^y}{\partial v}(y^3 - \bar{y}^3) + \frac{\partial p^x}{\partial v}(x^3 - \bar{x}^3) + \tau\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v}\right)\right] \tag{8}$$

In this case, we see that part (*d*) in equation (6) has disappeared, and the optimal consumption tax (for regions 1 and 2 jointly) is positive if region 3 is not a net importer of the good y.

2.2.2. The global welfare maximization

Let us now assume that the planer in region 1 is concerned about the global welfare when imposing a unilateral climate policy in region 1, including the cost of emissions as before. Global welfare can then be expressed as followed:

$$W^G = \sum_{j=1,2,3}\left[u^j\left(\bar{x}^j, \bar{y}^j, \bar{z}^j\right) - c^{xj}\left(x^j\right) - c^{yj}\left(y^j, e^{yj}\right) - c^{zj}\left(z^j, e^{zj}\right) - \tau^1\left(e^{yj} + e^{zj}\right)\right] \tag{9}$$

where τ^1 is still region 1's valuation of global emissions, referred to as the Pigouvian tax above.

By differentiating w.r.t. to the consumption tax in region 1 (given a joint quota market with OBA in regions 1 and 2), we find that:[9]

$$v^{1G*} = \underbrace{\left(\frac{\partial \bar{y}^1}{\partial v^1}\right)^{-1}}_{f} \left[\underbrace{s\left(\frac{\partial y^1}{\partial v^1} + \frac{\partial y^2}{\partial v^1}\right)}_{g} + \tau^1 \underbrace{\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v^1}\right)}_{h}\right] \tag{10}$$

From previously, we know that *(f)* is negative, $\frac{\partial \bar{y}^1}{\partial v^1} < 0$, as a consumption tax causes less demand in region 1.

Furthermore, the global market price for good y falls because of less demand and the price reduction makes it less profitable for the producers in the international market, hence ***(g)*** must be negative as well, $\frac{\partial y^1}{\partial v^1}, \frac{\partial y^2}{\partial v^1} < 0$. This is similar to part (*b*) in equation (6).

The last terms is identical to the last term in (6), which we argued is negative, cf. equation (7).

The social planner in region 1 was earlier concerned about the terms-of-trade effects when maximizing welfare in region 1, while this is not the case when it takes a global welfare perspective. Moreover, part (*d*) in equation (6) is also no longer present in equation (9) as the planner takes into account effects on production costs in region 2 as well.

Thus, we see that from a global welfare perspective, the optimal consumption tax in region 1 is unambiguously positive. We state this as a proposition:

Proposition 2. Consider a region i that has a joint emission trading system with another region j, where output-based allocation is implemented for production of EITE-goods. Then it is optimal from a global welfare perspective that region i impose a consumption tax on EITE-goods.
Proof: The proof follows from the discussion of equation (9) above.

[9] See Appendix A2

Last, consider the case if region 3 is unaffected by the consumption tax in region 1[10]. Equation (9) then becomes:

$$v^{1G*} = \frac{s\left(\frac{\partial y^1}{\partial v^1} + \frac{\partial y^2}{\partial v^1}\right)}{\left(\frac{\partial \bar{y}^1}{\partial v^1}\right)}$$

Since consumption of y in region 2 is likely to increase as a result of the consumption tax in region 1 (via lower price of the y good), the numerator is likely smaller than the denominator. Thus, we have $v^{1G*} < s^1$. However, the less consumption in region 2 responds to the reduced consumption in region 1, the higher is v^{1G*}. Moreover, if we return to the case with two regions (or implement the consumption tax in both regions 1 and 2), the optimal consumption tax becomes equal to the OBA subsidy: $v^{1G*} = s^1$. The latter supports the findings from Böhringer et al. (2017) when a Pigouvian tax is implemented on top of the OBR, in a two regions case.

3. Numerical analysis

Based on the theoretical model, we now transfer our analysis to numerical simulations. Numerical simulations are useful to examine the ambiguous outcomes from our theoretical analysis, while also give more in-depth insights into the proportion of economic effects based on empirical data. We are particularly interested in the case of Norway, which has a joint emission trading system with the European Union (EU ETS), where a variant of output-based allocation is already in place for emission-intensive goods. Our main question here is whether it is welfare-improving for Norway to implement a consumption tax on such goods, when the effects on global emissions are also taken into account.

3.1 Model summary

We assume three regions calibrated according to Norway (NOR), the European Union (EU) and rest of the world (ROW). The three regions have the same three production sectors as in our theoretical model in Section 2: non-carbon and tradable production x, carbon-intensive and tradable production y, and carbon-intensive and non-tradable production z. These goods can only be used in final consumption. As in the

[10] This could be the case if there is no trade between regions 1-2 and region 3, or if region 3 is much smaller than regions 1-2, in which case production and consumption changes in regions 1-2 are much bigger than in region 3.

theoretical model, the tradable goods are assumed homogenous with a global price and no transportation cost.

Each region's final consumption is determined by a representative agent who maximizes utility subject to a budget constraint. The representative agent's budget constraint is simply the balance of payment constraint fixed to the calibrated Business-As-Usual (BAU) level, and the agent's utility is given as a constant-elasticity-of-substitution (CES) combination of final consumption goods.

3.2 Data and calibration

We use the standard calibration procedure in numerical simulation analysis, where base-year data information defines some of the exogenous parameter values. For other parameters, we either use estimates from other studies, calibrate them based on simulations of a well-established large-scale CGE-model (Böhringer et al., 2017), or use educated guesses (see below for details).

The calibration of the model is based on World input Output Database (WIOD) data (base-year 2009)[11]. In order to closely relate our numerical analysis with the theoretical part, we restructure the empirical data to fit the model in Section 2. The WIOD-dataset of the world is based on 43 regions with 56 sectors, linked with corresponding data of CO_2-emission from each sector.[12] We map all the WIOD sectors into three merged sectors x, y and z, following the same notations from our theoretical analysis.[13] Further, we stick to the presumption in the theoretical analysis that there are no carbon related emissions in sector x, and thus set emissions in this sector equal to zero.[14]

We observe and quantify net exports in sector x and y in the base-year based on the difference between a region's production and consumption. As mentioned before, we assume no trade for the z sector. The calibrated z sector, however, is a composite of some sectors with limited trade. Thus, 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 on share form with share parameters of consumption set to base-year shares. Like Böhringer et al. (2017), we use a substitution elasticity of 0.5 between the three goods, and assume perfect substitution between locally produced and imported goods.

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[11] The model is implemented as a Mixed Complementarity Problem in GAMS, using the PATH-solver.
[12] CO_2-data for Norway is collected from Statistics Norway (SSB).
[13] See appendix B for mapping of WIOD sectors.
[14] In our dataset, sector x accounted for 14-15% of the global CO_2 emissions in 2009.

The cost function for the profit-maximizing producer is consistent with the assumptions from the theoretical model. We consider the following functional form (where we use x as an example):

$$cost^{x^j} = \frac{x^{j^{\beta}}}{\left(\kappa_1{}^j + \kappa_2{}^j\left(\frac{e^{x^j}}{x^j}\right) - \kappa_3{}^j\left(\frac{e^{x^j}}{x^j}\right)^2\right)} \tag{11}$$

As before, x^j is the produced amount of good x in region j, and e^{x^j} is the emission from producing good x in region j. The parameter β determines how quickly marginal production costs increase with increasing production. In our base case simulation, we set $\beta = 1.1$, meaning that production has almost constant returns to scale.[15] $\kappa_1{}^j$, $\kappa_2{}^j$ and $\kappa_3{}^j$ are parameters which are (uniquely) calibrated so that the following three conditions hold: i) marginal production costs in the base-year are equal to the base-year prices, ii) marginal abatement costs are equal to zero in the base-year, and iii) marginal abatement costs equal to \$10 per ton CO_2 correspond to θ^j % reduction in emission intensity, where θ^j is calibrated by simulating the multi-regional, multi-sectoral CGE model used by Böhringer et al. (2018).[16] Values of θ^j and κ_n^j are shown in Table 1, together with base-year levels of production and consumption in the different sectors and regions.

	θ^j	κ_1^j	κ_2^j	κ_3^j	*Production (billion \$)*	*Consumption (billion \$)*	*CO_2 (billion ton)*
x^{NOR}	-	2.01	-	-	422	448	-
y^{NOR}	1.6%	1.76	1 270	4.86×10^6	179	111	2.34×10^{-2}
z^{NOR}	3.8%	1.51	467	5.51×10^5	46	46	1.95×10^{-2}
x^{EU}	-	3.02	-	-	24 645	24 162	-
y^{EU}	1.6%	2.41	1 767	4.89×10^6	4 846	5 000	8.76×10^{-1}
z^{EU}	3.8%	2.04	679	3.77×10^5	1 952	1 952	1.76
x^{ROW}	-	3.31	-	-	60 160	60 166	-
y^{ROW}	5.0%	2.86	649	1.21×10^6	19 301	19 214	5.16
z^{ROW}	6.3%	2.25	457	1.40×10^5	5 820	5 820	9.49

Table 1: Base-year values from WIOD data and calibrated parameters in the numerical model

3.3 Policy scenarios

We consider the calibrated equilibrium in 2009 as a business-as-usual scenario, even though the EU ETS was already in place with an average ETS price of 13 Euro per ton CO_2 in 2009. Norway joined the EU ETS in

[15] This parameter is chosen simply to get a reference scenario that gives leakage rates within the range of most previous CGE studies of carbon leakage. In the sensitivity analysis, we consider alternative values of this parameter.
[16] Norway and the EU are not separate regions in the CGE model, so we assume the same θ^j for these two regions.

2008. Our reference (*REF*) policy scenario is when Norway and the EU together achieve a joint emission reduction target for the whole economy, using an economy-wide ETS with either auctioning or unconditional grandfathering. The reduction target is set to 20 percent in the main scenarios.[17] Next, we consider the scenario where producers of the y good receive allowances in proportion to their output, i.e., output-based allocation (*OBA*). We assume that the number of free allowances to y producers is chosen so that the net purchase of allowances for y producers is zero, i.e., $s(y^1 + y^2) = t(e^{y1} + e^{y2})$. Then we consider scenarios where Norway implements a carbon consumption tax on the y good (*OBA+Tax*). Whereas both OBA and the consumption tax are directed towards the emission-intensive and trade-exposed sector y, sector z will still be competing for the available permits after the additional policies are adopted. In the *OBA+Tax* scenarios we consider different levels of the consumption tax, ranging from 0% to 200% as a fraction of the OBA rate s.

Since global emissions are different across the policy scenarios, we need to put a price on global emission reductions (as in Section 2). For the most part, we will assume that the permit price in the REF scenario reflects Norway's valuation of global emission reductions.

To examine the sensitivity of our findings, the sensitivity analysis involves different substitution elasticities in the utility function for the representative agent.

3.4 Results

We investigate the effects on key indicators such as leakage rate, welfare, permit price and production. The leakage rate is defined as percentage changes in the non-abating region's (ROW) emission, over emissions reduction in the abating regions (NOR+EU). The welfare change measure is the ratio between BAU and the different policy scenarios, where regional welfare is defined as in equation (5). Thus, the welfare metric also takes into account the change in global emission level.

[17] Given the existence of the EU ETS in 2009, we can think of this as an additional emission reduction target of 20 percent relative to the base-year emission. The permit price are reported in this chapter without taking into account the 13 Euro per ton CO_2 in 2009.

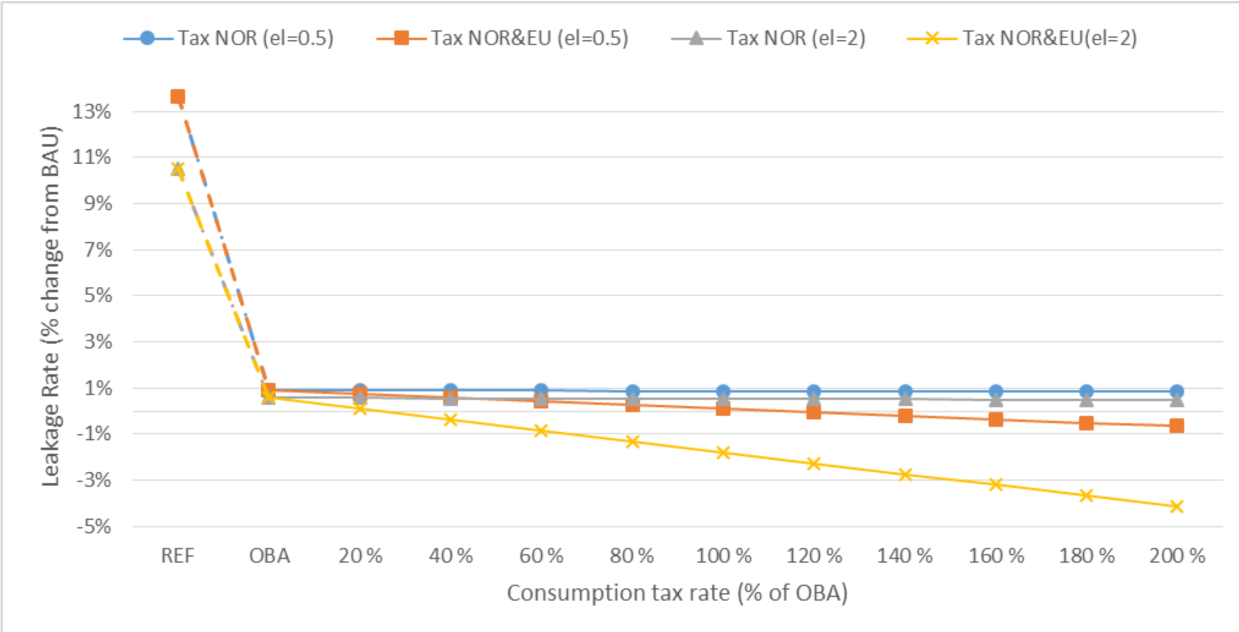

Figure 1: Leakage rate under different combination of policies and different elasticities

Figure 1 shows the effects on leakage in the different scenarios. In the *REF* scenario, with only emission pricing, the leakage rate is 11-13%, depending on the substitution elasticity in consumption. The leakage rate is lower with higher substitution elasticities, as this tends to shift consumption more towards the carbon-free good x. Given no energy trade in our model, leakage only happens through the market for EITE-goods (y). Hence, the leakage rate in *REF* is relatively high, which is due to the assumption of homogenous goods. Next, the figure shows that introducing *OBA* has significant impact on leakage, which becomes close to zero under both substitution elasticities considered. That is, OBA provides almost perfect leakage mitigation in our model. With consumption tax gradually introduced in Norway, the leakage rate continues to decrease, but only slightly as Norway constitutes a small part of the abating regions.[18] The leakage rate decreases somewhat more rapidly with higher elasticity of substitution, which again is due to a larger change in consumption towards other goods than the y good when consumption of the latter good is taxed in Norway. The figure further shows that introducing a consumption tax in both regions clearly has a bigger impact on the leakage rate, especially with higher substitution elasticity.

[18] Recall that the leakage rate is measured as emission changes in ROW divided by emission reductions in EU+NOR.

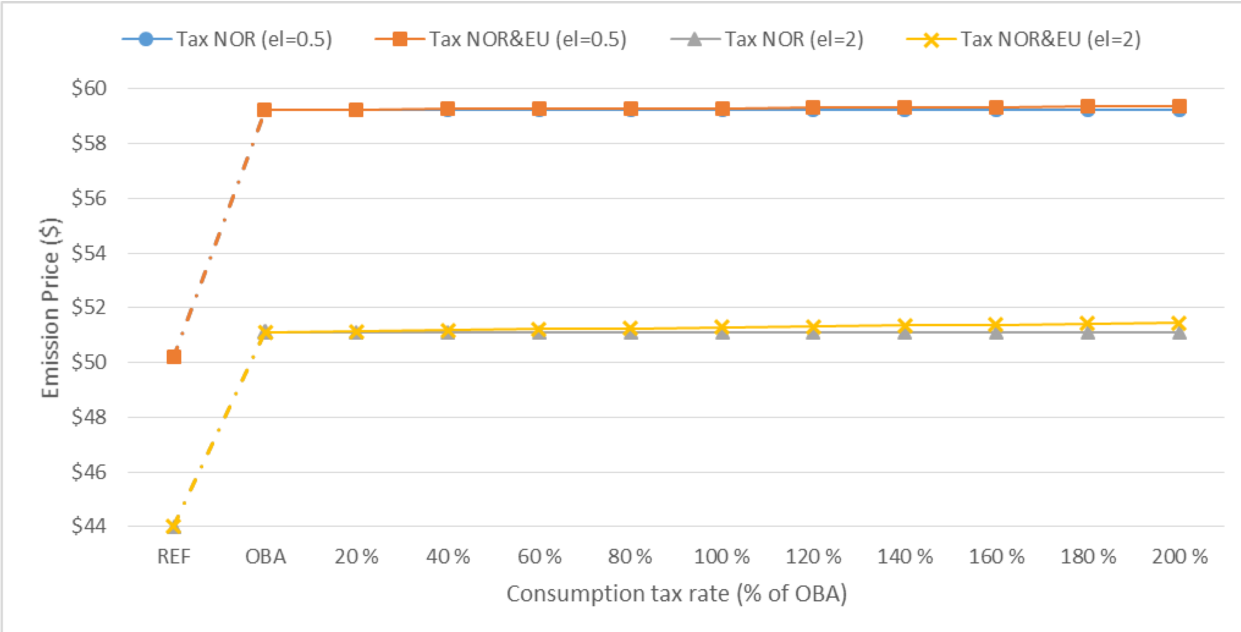

Figure 2: Emission price under different combination of policies and CES elasticities

As stated earlier, the OBA tends to simulate local production of the y good, while the consumption tax reduces the demand for the same good. This has implications for the permit market in EU and Norway, and hence for the permit price. Figure 2 shows that the permit price increases under OBA, as expected: With more output of the y good produced domestically, the permit price must increase in order to clear the permit market. With gradually increasing consumption tax, we would expect the permit price to decrease due to less production of the y good, but the permit price increases (marginally). This could be explained by the following.

The consumption tax dampens demand for good y in Norway, and increases Norway's net export of y. Less demand leads to a slightly lower price, and hence demand in EU and ROW increases for good y. The net effect is still less global production and consumption of good y, as lower prices makes it less profitable for the firms to produce the y good. More permits are then available, which tends to reduce the permit price as a first order effect, reducing the costs for sector z. With a CES utility preference and a balance-of-payment constraint, more of the agent's income is now spent on the relatively cheaper goods x and z in Norway. EU as the only net exporter of good x (in all scenarios), increases its overall consumption as beneficial terms-of-trade effects result in greater income and thus more expenditures on all goods. This further stimulates production of the z good also in the EU, which tends to increase the permit price. Due to the terms-of-trade effects, this second order effect seems to be marginally stronger than the first order effect.[19]

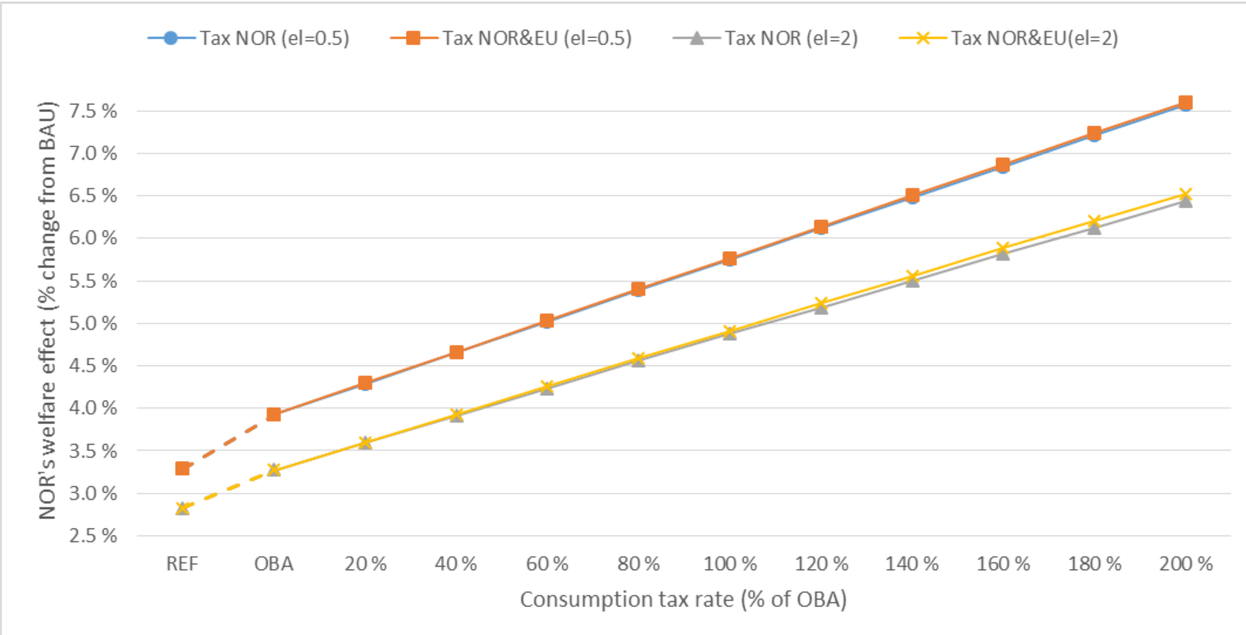

Figure 3: Norway's welfare effect under different combination of policies and CES elasticities

Figure 3 shows the welfare change in Norway under the different policies. The change is displayed as a percentage change compared to the BAU scenario, also taking into account the change in global emissions, where we use the emission price from *REF* to value these changes. As discussed in Section 2, the marginal cost of emissions τ could be different from the permit price t. Thus, a sensitivity analysis is carried out with different marginal cost of emission τ in the following section.

The OBA reallocates production from ROW back to the abating regions. Further, global emissions decline under the OBA scenario compared to *REF*, meaning less climate damages. The overall results indicate a welfare improving effect of OBA in Norway. This supports previous findings in e.g. Böhringer et al. (2017), when assuming homogenous tradable goods. The theoretical analysis in Section 2 suggested ambiguous effects on welfare for a region that implements a consumption tax. Our numerical simulation however suggests that the consumption tax is welfare improving in Norway, and monotonically improves welfare as the tax rises until at least 200% of the OBA-rate. The improvement for Norway is marginally greater if both abating regions introduces the tax, and slightly smaller when assuming a higher substitution of elasticity. The

[19] To check this argument, we ran a simulation with climate policy in ROW instead of EU+NOR. When implementing a consumption tax on top of OBA in ROW, the permit price is steadily decreasing as expected. Thus, it seems that the terms-of-trade effects in EU are explaining the counter-intuitive effects on the permit price.

main drivers for the welfare improvement in NOR seems to be the positive emission and terms-of-trade effects.

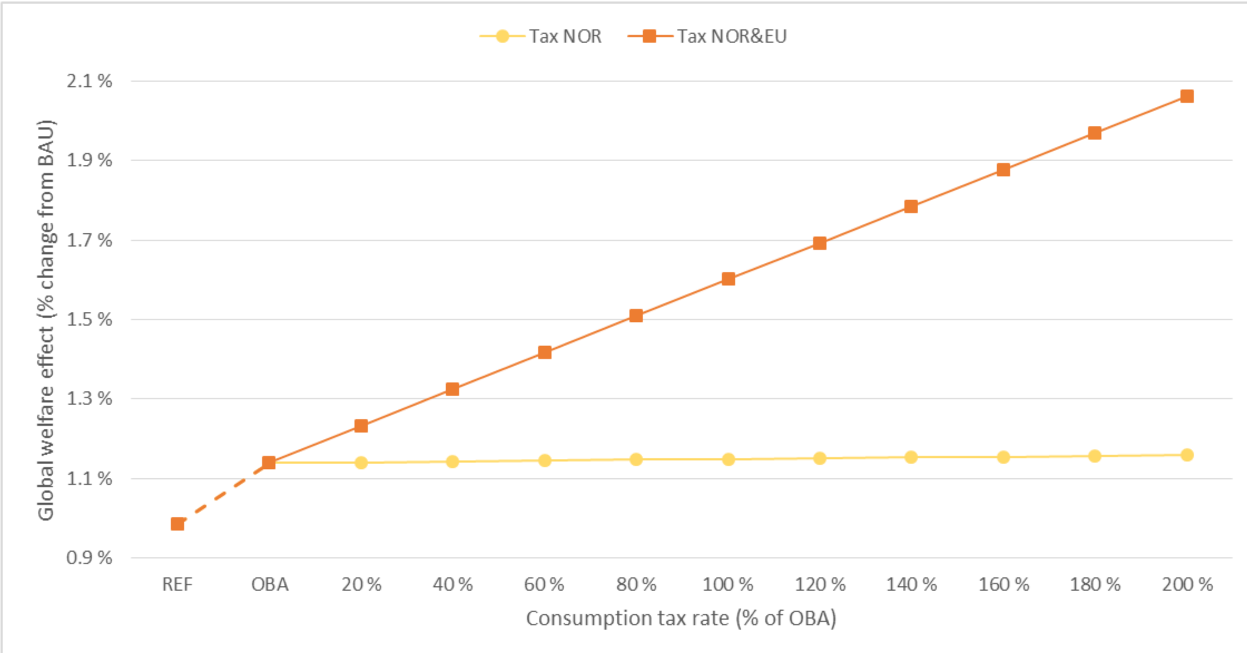

Figure 4: Global welfare effects under different combination of policies

According to our proposition 2, a consumption tax on top of the OBA in Norway, has an unambiguously positive effect from a global welfare perspective. Results illustrated in Figure 4 support this presupposition, and suggest further beneficial improvements by increasing the tax rate (at least until 200% of the OBA-rate). Naturally, the global welfare improvement is much stronger if both abating regions introduce the tax, and again the welfare effects are slightly smaller when assuming a higher substitution of elasticity.

Figure 5 shows the welfare gains for EU and ROW with substitution elasticity of 0.5 on the demand side. In the case where the consumption tax is imposed in both the EU and Norway, we notice that the EU benefits from this (just like Norway, see Figure 3). In this case, we further see that ROW loses.[20] Hence, the global welfare improvement shown in Figure 4 is partly due to the fact that Norway and the EU gains from terms of trade effects at the expenses of ROW. The welfare effect in ROW is also (slightly) negative when a consumption tax is introduced only in Norway. This result supports similar findings in Böhringer et al. (2017). It is however important to emphasize that overall global welfare effects from the consumption tax are unambiguously positive, and thus in principle at least all regions could be better off if ROW were to be compensated through a monetary transfer.

[20] We assume that $\tau^{ROW} = 0$ in ROW's welfare function, as there is no climate policy in this region (in our analysis).

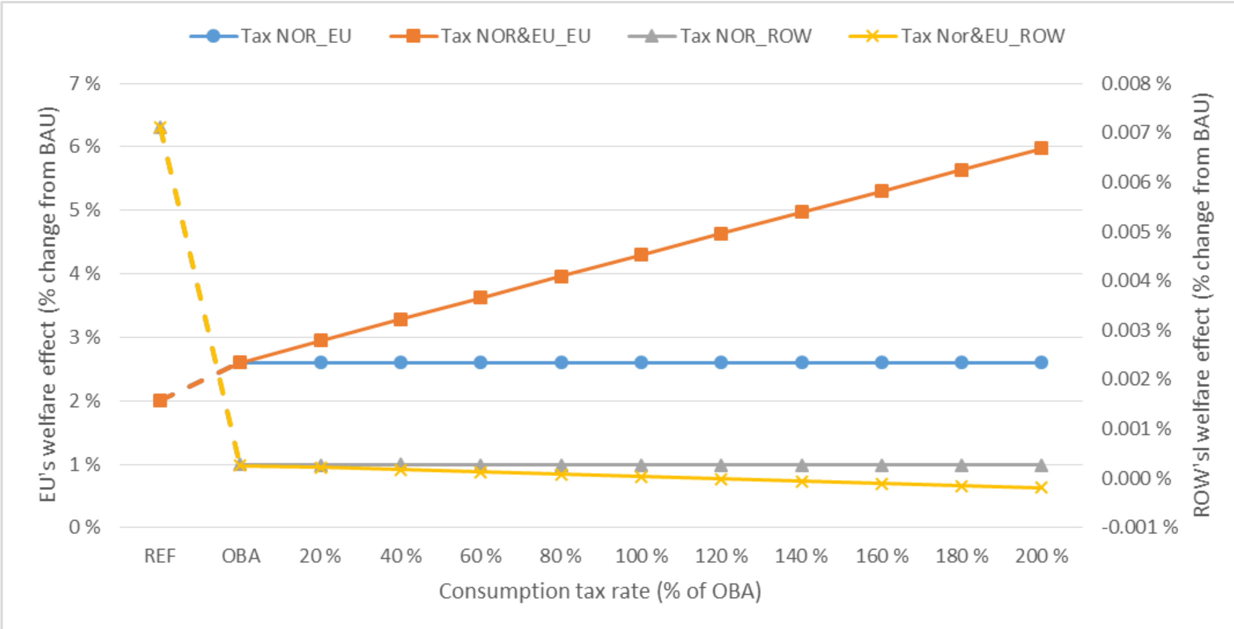

Figure 5: ROW and EU's welfare effects under different combination of policies and CES elasticities

The effects on consumption in Norway is shown in Figure 6, under different combinations of policies where the consumption tax is only introduced in Norway. Here the substitution elasticity is set equal to 0.5. A carbon price (REF) increases the costs for the producers of carbon intensive goods y and z in Europe, and hence the price of these goods, which further reduces the demand for y and z in Norway (and the EU). Because of the low substitution elasticity between the three goods (goods can only be used in final consumption in our model), and worsened terms-of-trade effects, consumption of the carbon-free good x also declines. When OBA is introduced for the good y, we have the opposite effect for this good as OBA works as an implicit production subsidy to y. Again, due the low substitution elasticity and improved terms-of-trade effects, demand for the two other goods increase as well, but not as much as for y. Consumption of y and x is higher than the BAU-level under OBA, while consumption of z is somewhat lower. When the consumption tax is introduced on good y, we see that the consumption of y decreases significantly, while consumption of x and z increases. Consumption of z is always below the BAU scenario, however, in our results. The increased consumption of x and z is due to the relative price changes and improved terms-of-trade effects. More of the y good is now exported from Norway and more is imported of x.

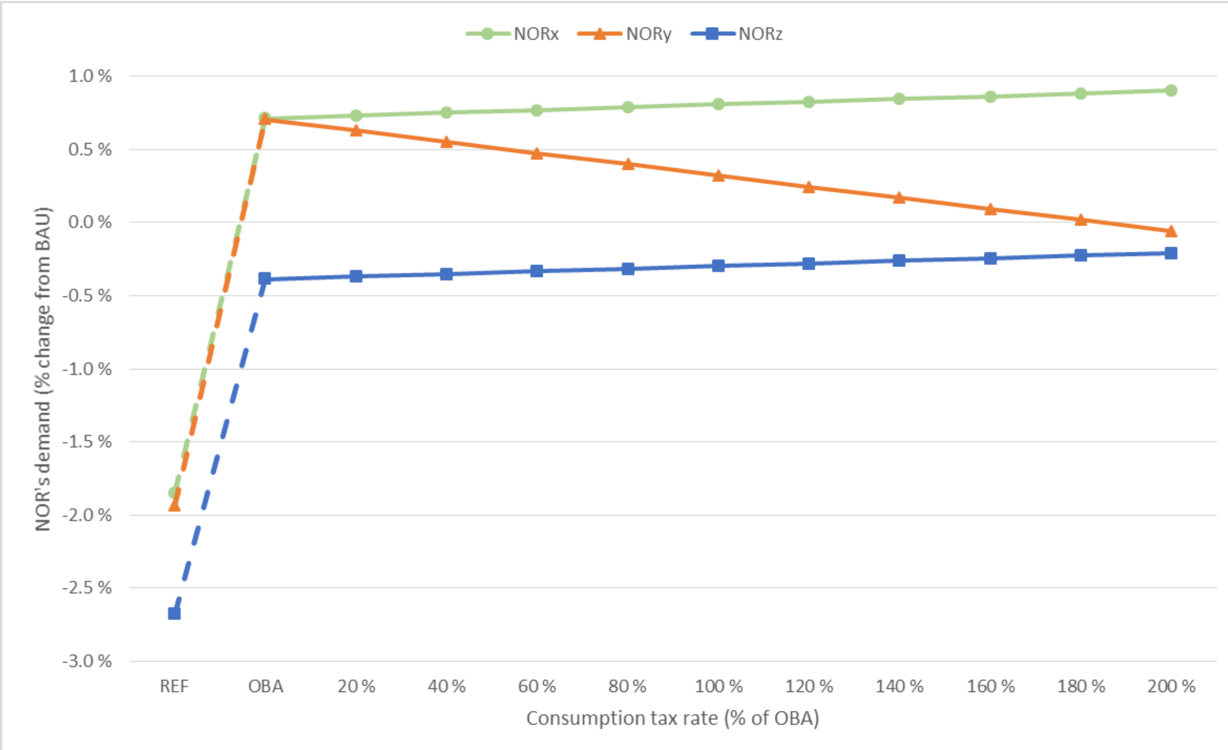

Figure 6: Consumption of the three goods in Norway under different combination of policies

3.5 Sensitivity analysis

How robust are our numerical results with respect to changes in our model assumptions? For instance, the theoretical analysis showed that regional welfare effects for the tax-implementing region are ambiguous, while the numerical simulations showed a positive effect for Norway. Furthermore, the simulations confirmed the unambiguous theoretical result that global welfare improves. To check the robustness of the results, we now examine the effects of changing some of our main assumptions: i)the convexity of the cost function, ii) the costs of reducing emissions from the production of the goods y and z,(in all regions), iii) a scenario with the optimal *Pigouvian* tax being higher than the emission price in REF, iv) heterogeneous goods, where domestic and foreign goods are distinguished by origin, v) and a consumption tax introduced in other European countries than Norway.

Table 2 shows the effects on Norwegian welfare of alternative combinations of i) substitution elasticity and ii) convexity parameter in the cost functions. All tests are conducted with OBA introduced in both regions, while the consumption tax (equal to the OBA-rate) is only implemented in Norway. The substitution elasticities are the same as in Section 3.4 (0.5 and 2), while the cost parameter β from equation (10) is set to 1.1, 1.3 and 1.5. We see from the table that the robustness tests support the finding from the benchmark analysis, i.e., that welfare in Norway is consistently increasing under all these alternative assumptions. The magnitude clearly differs, and the biggest welfare gains are achieved when both the substitution elasticity and the cost parameter are low. The effects on global welfare, which are not shown in the table, are also consistently (marginally) positive, and leakage rates are consistently (marginally) falling, thus reducing the global emissions compared to the *OBA* scenario.

Elasticity of substitution	***Cost parameter β***	***OBA Welfare (NOR)***	***OBA & 100% consumption tax Welfare (NOR)***
0.5	**1.1**	***3.9%***	***5.8%***
0.5	1.3	*1.6%*	*2.4%*
0.5	1.5	*1.1%*	*1.7%*
2.0	**1.1**	***3.3%***	***4.9%***
2.0	1.3	*1.3%*	*2.0%*
2.0	1.5	*0.9%*	*1.3%*

Table 2: Regional welfare effects of alternative combinations of substitution elasticity and the cost parameter β. Percentage changes vis-à-vis BAU

Table 3 shows the same support for our findings with different assumptions about marginal abetment costs. That is, with twice as high marginal abatement costs for the producers of goods y and z (in all regions), the consumption tax still increases Norwegian welfare. The increase is higher than in the benchmark simulations. Again, leakage decreases after implementing the consumption tax, and global welfare also improves. The results suggest that the higher the marginal costs of abatement, the greater the advantageous impacts of a consumption tax on welfare and leakage.

In our theoretical analysis, we discussed the possibility of the *Pigouvian* tax being different from the carbon price observed in the REF scenario (in the benchmark simulations, we have assumed that the two are equal). In particular, given the low prices in the EU Emission Trading System over the last years, one could argue that the Pigouvian tax is higher than the current CO_2 price. Table 3 shows that if the *Pigouvian* tax is 50 % higher than the REF carbon price, the benefits of the climate policy would naturally be bigger as global emission reductions would have a greater impact on welfare (the size of the emission reductions would be the same as in the benchmark simulations). The additional welfare gains from the consumption tax are however about the same as in the benchmark simulations.

Alternative assumptions	***OBA*** ***Welfare (NOR)***	***OBA & 100% consumption tax*** ***Welfare (NOR)***
Benchmark results (subst.elast. = 0.5)	***3.9%***	***5.8%***
Higher marginal abatement costs	*6.8%*	*10.3%*
Pigouvian tax > carbon price	*5.2%*	*7.1%*

Table 3: Regional welfare effects of alternative assumptions about abatement costs and Pigouvian tax. Percentage changes vis-à-vis BAU

Next, we 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 we distinguish between domestic and foreign produced goods ("Armington goods"). At the top level in the utility function, we keep the same assumption as before when it comes to substitution between the goods x, y and z. At the second level, we incorporate substitution between domestic and imported goods x and y, and at the third level we distinguish between the origin of the foreign produced goods.[21] In Figure 7 we show how this assumption affects welfare globally and in Norway compared to the homogenous goods case. The welfare effects under all the different policy scenarios are higher with Armington goods than with the homogenous goods. This is mainly a result of leakage now being more limited, and therefore the global benefits of emission reductions are bigger. With substitution possibilities between domestic and foreign goods being more limited, leakage becomes less of a concern, and thus the negative effects of the implicit subsidy of *OBA* become dominating. That is, moving from *REF* to the *OBA* scenario with Armington goods leads to lower welfare effects in Norway. The numerical simulations still suggest, however, that the consumption tax is welfare improving for Norway, and that welfare improves as the tax rises. The global welfare effects are also positive under all the different scenarios, but still limited with only Norway introducing the consumption tax. Figure 7 furthermore shows that the global welfare effects are in general higher with Armington goods than in the homogenous goods case, but moving from *REF* to *OBA* has smaller global welfare gains.

[21] We assume a substitution of elasticity at the top level of 0.5 (as before), at the second level of 4, and 8 at the third level. With an infinite Armington elasticity settings on the second and third levels, the heterogeneous goods case transforms into the case of homogenous goods.

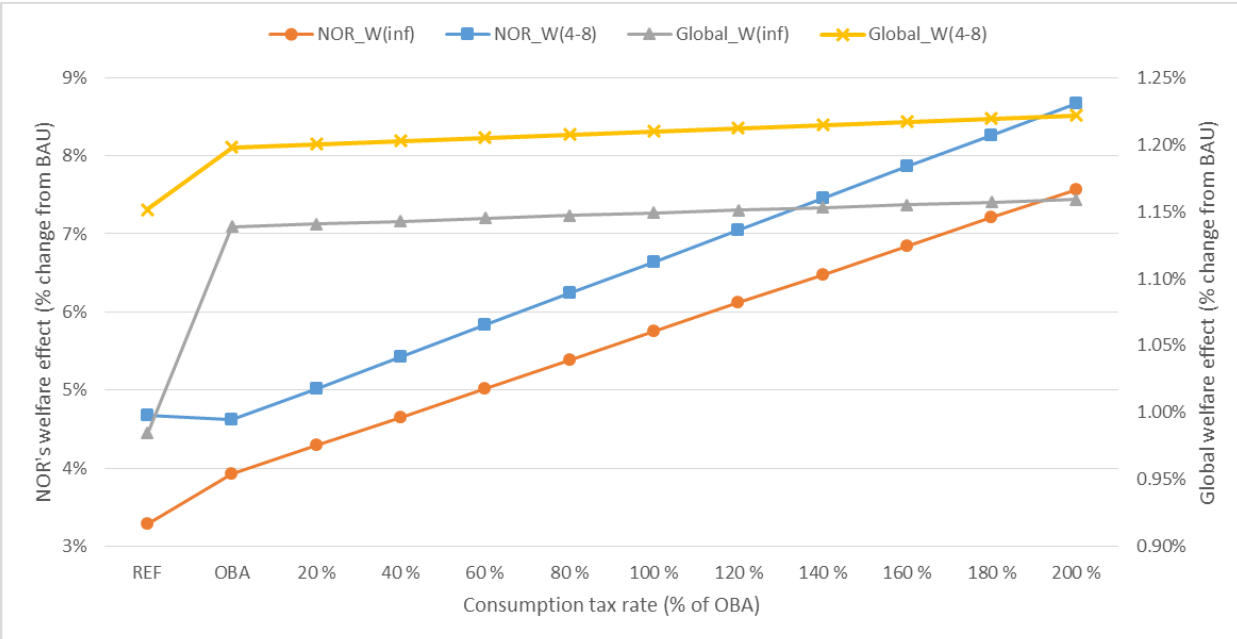

Figure 7: Comparing global and Norway's welfare effects between homogenous goods (*inf*) and Armington goods (*4-8*).

How would a consumption tax introduced in another EU/EEA country than Norway affect both the regional and global welfare? In Table 4 we list the result under various combination of policies in different EU countries. In the model, we replace the region Norway with an EU country, and include Norway in the EU region. The parameters in the model are calibrated in the same way as described in section 3.2, i.e., according to the specific country's characteristics. The substitution elasticity is here set to 0.5. The table shows the same qualitative result as for Norway, when different EU countries introduce the consumption tax. That is, a consumption tax on top of OBA consistently increases regional welfare. The welfare effect is positive when going from *BAU* to *REF*, from *REF* to *OBA*, and from *OBA* to *OBA* with a consumption tax. Global welfare increases too in all these cases. The magnitude differs from a marginally to significantly positive effect and depends on the policy introducing country's economic size. That is, the bigger the economic size of the country, the more significant the impact on global welfare. In line with our finding from section 3.4, the positive effect on welfare from the consumption tax is most likely due to the positive emission effect. For some of the smallest economies in the EU, the regional welfare gain is substantial compared to *BAU*. The reason is first of all their relatively small economic size, which makes the welfare gain from a positive emission effect much stronger. Remember that when going from *BAU* to *REF*, the whole EU reduces its emissions. Secondly, they are all net-importer of the y good, so a climate policy improves their terms-of-trade.

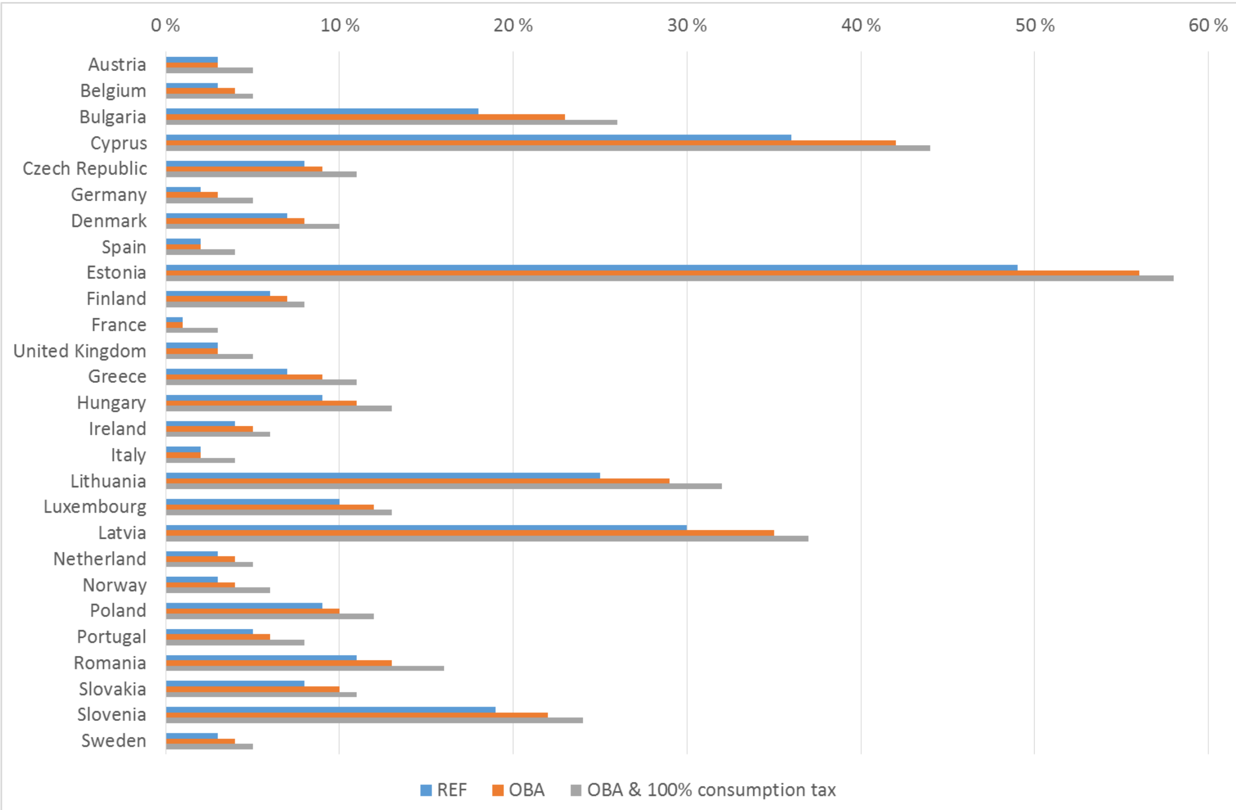

Figure 8: Regional welfare effects under different combination of policies in EU countries. Percentage changes vis-à-vis BAU

4. Concluding remarks

As the world will still rely on unilateral action after the Paris climate agreement, many countries are considering or have introduced climate policies such as emission trading systems. Greenhouse gases however are global pollutants and unilateral action leads to carbon leakage when there is no global cap on emissions. In this paper we have focused on leakage associated with the relocation of emission-intensive and trade-exposed (EITE) industries. The economics literature have suggested different approaches to mitigate this type of carbon leakage, where border carbon adjustment in addition to emission pricing has been regarded as a second-best instrument to improve cost-effectiveness of unilateral climate policy. This instrument may not however be politically feasible, so countries and regions have either excluded such industries from their regulations or found other anti-leakage solutions, such as output-based allocation (OBA) to EITE-industries, which has been implemented e.g. in the EU ETS.

However, as OBA acts as an implicit production subsidy to domestic production, this results in too high consumption and production worldwide. Hence, an approach where OBA is combined with a consumption tax on all use of the EITE goods has been proposed by e.g. Böhringer et al. (2017). In the current paper we have examined whether a single country, being part of a bigger ETS involving many countries where OBA to EITE-industries is already in place, should unilaterally implement such a consumption tax.

We first showed analytically that under certain conditions it is welfare improving for the single country to introduce the consumption tax, when we account for the benefits of reduced global emissions. Moreover, the consumption tax has an unambiguous global welfare improving effect. Next, we confirmed these results with a stylized numerical model calibrated to real world data, where we considered the context of the EU ETS. Individual EU/EEA members were consistently better off in welfare terms if implementing such a consumption tax.

If the tax is set equal to the output-based allocation factors ("benchmarks"), the administrative cost of adding such a consumption tax will likely be limited (Neuhoff et al., 2016a; Ismer and Haussner, 2016). Böhringer et al. (2017) shows that the outcome of this combined policy will be equivalent to a certain variant of border carbon adjustments. Thus, combining output-based allocation with a consumption tax seems like a powerful policy strategy to mitigate carbon leakage, also for individual countries involved in a more extensive emission trading system

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Appendix A, Derivations

A1: Region welfare maximization

By differentiating the regional welfare (5) with respect to consumptions tax, we get

$$\frac{\partial W^1}{\partial v^1} = u_x^1\frac{\partial \bar{x}^1}{\partial v^1} + u_y^1\frac{\partial \bar{y}^1}{\partial v^1} + u_z^1\frac{\partial \bar{z}^1}{\partial v^1} - c_x^{x1}\frac{\partial x^1}{\partial v^1} - c_y^{y1}\frac{\partial y^1}{\partial v^1} - c_z^{z1}\frac{\partial z^1}{\partial v^1} - c_e^{y1}\frac{\partial e^{y1}}{\partial v^1} - c_e^{z1}\frac{\partial e^{z1}}{\partial v^1} - \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

Recall the conditions and assumptions from (2) and (3), and we then get

$$= p^x\frac{\partial \bar{x}^1}{\partial v^1} + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1} + p^{z1}\frac{\partial \bar{z}^1}{\partial v^1} - p^x\frac{\partial x^1}{\partial v^1} - (p^y + s^1)\frac{\partial y^1}{\partial v^1} - p^{z1}\frac{\partial z^1}{\partial v^1} + t^1\frac{\partial e^{y1}}{\partial v^1} + t^1\frac{\partial e^{z1}}{\partial v^1}$$
$$- \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

We further simplify the equation

$$= p^x\frac{\partial \bar{x}^1}{\partial v^1} - p^x\frac{\partial x^1}{\partial v^1} + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1} + p^{z1}\frac{\partial \bar{z}^1}{\partial v^1} - p^{z1}\frac{\partial z^1}{\partial v^1} - (p^y + s^1)\frac{\partial y^1}{\partial v^1} + t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right)$$
$$- \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

$$= p^x\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right) + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1} + p^{z1}\left(\frac{\partial \bar{z}^1}{\partial v^1} - \frac{\partial z^1}{\partial v^1}\right) - (p^y + s^1)\frac{\partial y^1}{\partial v^1} + t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right)$$

$$- \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

Since there is no trade of the good z, i.e. $\left(\frac{\partial \bar{z}^1}{\partial v^1} = \frac{\partial z^1}{\partial v^1}\right)$:

$$= p^x\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right) + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1} - (p^y + s^1)\frac{\partial y^1}{\partial v^1} + t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right) - \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

Recall (4), further we differentiate (4) w.r.t. consumption tax, remembering the product rule:

$$\frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + p^y\left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1}\right) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) + p^x\left(\frac{\partial x^1}{\partial v^1} - \frac{\partial \bar{x}^1}{\partial v^1}\right) = 0$$

solving this for p^x

$$p^x = \frac{\left(p^y\left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1)\right)}{-\left(\frac{\partial x^1}{\partial v^1} - \frac{\partial \bar{x}^1}{\partial v^1}\right)}$$

we insert this into our equation for p^x

$$\frac{\partial W^1}{\partial v^1} = \left[\frac{\left(p^y\left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1)\right)}{-\left(\frac{\partial x^1}{\partial v^1} - \frac{\partial \bar{x}^1}{\partial v^1}\right)}\right]\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right) + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1} - (p^y + s^1)\frac{\partial y^1}{\partial v^1} + t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right)$$

$$- \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

and since

$$-\frac{\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right)}{\left(\frac{\partial x^1}{\partial v^1} - \frac{\partial \bar{x}^1}{\partial v^1}\right)} = \frac{\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right)}{\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right)} = 1$$

We can further simplify:

$$= p^y\left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1} - (p^y + s^1)\frac{\partial y^1}{\partial v^1} + t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right)$$

$$- \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

$$= p^y\left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1} + \frac{\partial \bar{y}^1}{\partial v^1} - \frac{\partial y^1}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) + v^1\frac{\partial \bar{y}^1}{\partial v^1} - s^1\frac{\partial y^1}{\partial v^1} + t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right)$$

$$- \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

Recall the constraint on emission in region 1 and 2, $\bar{E} = e^{y1} + e^{y2} + e^{z1} + e^{z2}$. By differentiating this w.r.t the consumption tax, we have that:

$$\frac{\partial \bar{E}}{\partial v^1} = \frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} = 0$$

By this assumption, our equation can now be expressed as:

$$= p^y \left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1} + \frac{\partial \bar{y}^1}{\partial v^1} - \frac{\partial y^1}{\partial v^1} \right) + \frac{\partial p^y}{\partial v^1} (y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1} (x^1 - \bar{x}^1) + v^1 \frac{\partial \bar{y}^1}{\partial v^1} - s^1 \frac{\partial y^1}{\partial v^1} + t^1 \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} \right) - \tau \left[\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right]$$

and simplified to

$$= v^1 \frac{\partial \bar{y}^1}{\partial v^1} - s^1 \frac{\partial y^1}{\partial v^1} + \frac{\partial p^y}{\partial v^1} (y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1} (x^1 - \bar{x}^1) + t^1 \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} \right) - \tau \left[\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right]$$

And we finally arrive at (6), by moving v^1 on the other side of the equal sign

$$v^{1*} = \left(\frac{\partial \bar{y}^1}{\partial v^1} \right)^{-1} \left[s^1 \frac{\partial y^1}{\partial v^1} - \frac{\partial p^y}{\partial v^1} (y^1 - \bar{y}^1) - \frac{\partial p^x}{\partial v^1} (x^1 - \bar{x}^1) + (-t^1) \left(\frac{\partial e^{y1}}{\partial y^1} \frac{\partial y^1}{\partial v^1} + \frac{\partial e^{z1}}{\partial z^1} \frac{\partial z^1}{\partial v^1} \right) + \tau \left(\frac{\partial e^{y3}}{\partial y^3} \frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3} \frac{\partial z^3}{\partial v^1} \right) \right] \qquad (6)$$

A2: Global Welfare Maximization

By differentiating the global welfare w.r.t consumption tax in region 1, we get

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

From our assumption in (2), (3), (5) and (6) we get

$$\frac{\partial W^G}{\partial v^1} = \sum_{j=1,2,3} \left[p^x \frac{\partial \bar{x}^j}{\partial v^1} + \left(p^y + v^j\right) \frac{\partial \bar{y}^j}{\partial v^1} + p^{zj} \frac{\partial \bar{z}^j}{\partial v^1} - p^x \frac{\partial x^j}{\partial v^1} - \left(p^y + s^j\right) \frac{\partial y^j}{\partial v^1} - p^{zj} \frac{\partial z^j}{\partial v^1} \right] - \left(\tau + c_e^{y1}\right) \frac{\partial e^{y1}}{\partial v^1} - \left(\tau + c_e^{z1}\right) \frac{\partial e^{z1}}{\partial v^1}$$

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

$$= \sum_{j=1,2,3} \left[p^x \frac{\partial \bar{x}^j}{\partial v^1} - p^x \frac{\partial x^j}{\partial v^1} + \left(p^y + v^j\right) \frac{\partial \bar{y}^j}{\partial v^1} - \left(p^y + s^j\right) \frac{\partial y^j}{\partial v^1} + p^{zj} \frac{\partial \bar{z}^j}{\partial v^1} - p^{zj} \frac{\partial z^j}{\partial v^1} \right] - \left(\tau - t^1\right) \frac{\partial e^{y1}}{\partial v^1} - \left(\tau - t^1\right) \frac{\partial e^{z1}}{\partial v^1} - \left(\tau - t^2\right) \frac{\partial e^{y2}}{\partial v^1}$$

$$- \left(\tau - t^2\right) \frac{\partial e^{z2}}{\partial v^1} - \left(\tau + c_e^{y3}\right) \frac{\partial e^{y3}}{\partial v^1} - \left(\tau + c_e^{z3}\right) \frac{\partial e^{z3}}{\partial v^1}$$

Since good z is non-tradable, the production in region j is equal to consumption in the same region. Also recall that $c_e^{y3} = c_e^{z3} = 0$ and $t^1 = t^2$

$$= \sum_{j=1,2,3}\left[p^x\left(\frac{\partial \bar{x}^j}{\partial v^1}-\frac{\partial x^j}{\partial v^1}\right)+\left(p^y+v^j\right)\frac{\partial \bar{y}^j}{\partial v^1}+p^{zj}\left(\frac{\partial \bar{z}^j}{\partial v^1}-\frac{\partial z^j}{\partial v^1}\right)-\left(p^y+s^j\right)\frac{\partial y^j}{\partial v^1}\right]+(t^1-\tau)\left(\frac{\partial e^{y1}}{\partial v^1}+\frac{\partial e^{z1}}{\partial v^1}\right)+(t^1-\tau)\left(\frac{\partial e^{y2}}{\partial v^1}+\frac{\partial e^{z2}}{\partial v^1}\right)$$
$$-\tau\left(\frac{\partial e^{y3}}{\partial v^1}+\frac{\partial e^{z3}}{\partial v^1}\right)$$

Again, we use our assumptions from (4), differentiate w.r.t consumption tax and solve it for p^x (*remembering the product rule*):

$$\frac{\partial p^y}{\partial v^1}\left(y^j-\bar{y}^j\right)+p^y\left(\frac{\partial y^j}{\partial v^1}-\frac{\partial \bar{y}^j}{\partial v^1}\right)+\frac{\partial p^x}{\partial v^1}\left(x^j-\bar{x}^j\right)+p^x\left(\frac{\partial x^j}{\partial v^1}-\frac{\partial \bar{x}^j}{\partial v^1}\right)=0$$

$$p^x=\frac{\left(p^y\left(\frac{\partial y^j}{\partial v^1}-\frac{\partial \bar{y}^j}{\partial v^1}\right)+\frac{\partial p^y}{\partial v^1}\left(y^j-\bar{y}^j\right)+\frac{\partial p^x}{\partial v^1}\left(x^j-\bar{x}^j\right)\right)}{-\left(\frac{\partial x^j}{\partial v^1}-\frac{\partial \bar{x}^j}{\partial v^1}\right)}$$

Insert this for p^x into our equation:

$$\sum_{j=1,2,3}\left[\frac{\left(p^y\left(\frac{\partial y^j}{\partial v^1}-\frac{\partial \bar{y}^j}{\partial v^1}\right)+\frac{\partial p^y}{\partial v^1}\left(y^j-\bar{y}^j\right)+\frac{\partial p^x}{\partial v^1}\left(x^j-\bar{x}^j\right)\right)}{-\left(\frac{\partial x^j}{\partial v^1}-\frac{\partial \bar{x}^j}{\partial v^1}\right)}\left(\frac{\partial \bar{x}^j}{\partial v^1}-\frac{\partial x^j}{\partial v^1}\right)+\left(p^y+v^j\right)\frac{\partial \bar{y}^j}{\partial v^1}+p^{zj}\left(\frac{\partial \bar{z}^j}{\partial v^1}-\frac{\partial z^j}{\partial v^1}\right)-\left(p^y+s^j\right)\frac{\partial y^j}{\partial v^1}\right]$$
$$+(t^1-\tau)\left(\frac{\partial e^{y1}}{\partial v^1}+\frac{\partial e^{z1}}{\partial v^1}\right)+(t^1-\tau)\left(\frac{\partial e^{y2}}{\partial v^1}+\frac{\partial e^{z2}}{\partial v^1}\right)-\tau\left(\frac{\partial e^{y3}}{\partial v^1}+\frac{\partial e^{z3}}{\partial v^1}\right)$$

Since

$$\frac{\left(\frac{\partial \bar{x}^j}{\partial v^1} - \frac{\partial x^j}{\partial v^1}\right)}{\left(\frac{\partial \bar{x}^j}{\partial v^1} - \frac{\partial x^j}{\partial v^1}\right)} = 1$$

The equation can be simplified to

$$= \sum_{j=1,2,3} \left[p^y \left(\frac{\partial y^j}{\partial v^1} - \frac{\partial \bar{y}^j}{\partial v^1} \right) + \frac{\partial p^y}{\partial v^1} \left(y^j - \bar{y}^j \right) + \frac{\partial p^x}{\partial v^1} \left(x^j - \bar{x}^j \right) + \left(p^y + v^j \right) \frac{\partial \bar{y}^j}{\partial v^1} - \left(p^y + s^j \right) \frac{\partial y^j}{\partial v^1} \right] + (t^1 - \tau) \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} \right)$$
$$+ (t^1 - \tau) \left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} \right) - \tau \left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right)$$

$$= \sum_{j=1,2,3} \left[p^y \left(\frac{\partial y^j}{\partial v^1} - \frac{\partial \bar{y}^j}{\partial v^1} + \frac{\partial \bar{y}^j}{\partial v^1} - \frac{\partial y^j}{\partial v^1} \right) + \frac{\partial p^y}{\partial v^1} \left(y^j - \bar{y}^j \right) + \frac{\partial p^x}{\partial v^1} \left(x^j - \bar{x}^j \right) + v^j \frac{\partial \bar{y}^j}{\partial v^1} - s^j \frac{\partial y^j}{\partial v^1} \right] + (t^1 - \tau) \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} \right)$$
$$+ (t^1 - \tau) \left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} \right) - \tau \left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right)$$

$$= \sum_{j=1,2,3} \left[v^j \frac{\partial \bar{y}^j}{\partial v^1} - s^j \frac{\partial y^j}{\partial v^1} + \frac{\partial p^y}{\partial v^1} \left(y^j - \bar{y}^j \right) + \frac{\partial p^x}{\partial v^1} \left(x^j - \bar{x}^j \right) \right] + (t^1 - \tau) \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} \right) + (t^1 - \tau) \left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} \right) - \tau \left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right)$$

Recall our assumption from (1):

$$\bar{x}^1 + \bar{x}^2 + \bar{x}^3 = x^1 + x^2 + x^3$$

$$\bar{y}^1 + \bar{y}^2 + \bar{y}^3 = y^1 + y^2 + y^3$$

And we can rewrite our equation to

$$= \sum_{j=1,2,3} \left[v^j \frac{\partial \bar{y}^j}{\partial v^1} - s^j \frac{\partial y^j}{\partial v^1} \right] + (t^1 - \tau) \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} \right) + (t^2 - \tau) \left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} \right) - \tau \left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right)$$

Since the consumption tax is only introduced in region 1, and OBA in region 1 and 2, we can re-write to:

$$= \left(v^1 \frac{\partial \bar{y}^1}{\partial v^1} - s^1 \frac{\partial y^1}{\partial v^1} - s^2 \frac{\partial y^2}{\partial v^1} \right) + (t^1 - \tau) \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} \right) + (t^1 - \tau) \left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} \right) - \tau \left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right)$$

From (2) $s^1 = s^2$ and $t^1 = t^2$

$$v^{1G*} = \left(\frac{\partial \bar{y}^1}{\partial v^1} \right)^{-1} \left[s^1 \left(\frac{\partial y^1}{\partial v^1} + \frac{\partial y^2}{\partial v^1} \right) + (\tau - t^1) \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} \right) + \tau \left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right) \right]$$

Remembering our emission constraint $\frac{\partial \bar{E}}{\partial v^1} = \frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} = 0$, and we finally arrive at (9)

$$v^{1G*} = \left(\frac{\partial \bar{y}^1}{\partial v^1} \right)^{-1} \left[s^1 \left(\frac{\partial y^1}{\partial v^1} + \frac{\partial y^2}{\partial v^1} \right) + \tau \left(\frac{\partial e^{y3}}{\partial y^3} \frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3} \frac{\partial z^3}{\partial v^1} \right) \right] \tag{10}$$

Appendix B: 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
x: emission-free and tradable goods	All remaining goods and services

Table B1: Mapping of WIOD sectors to model sectors

Table B1 shows the mapping of the 56 WIOD sectors to three composite sectors in our model.