Unilateral climate policy and optimal containment in an open economy*

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Abstract

Without a broad international agreement, climate policy is less effective, due to carbon leakage, and more costly, due to causing unemployment and a loss of competitiveness on international markets. We investigate whether these negative effects can be addressed by partially containing the policy's effects to intermediate goods sectors, such as electricity or transportation services. We use a three-sector model to study a policy that taxes emissions caused by intermediate goods production while subsidizing the intermediate good. We show that such containment is second-best for combating carbon leakage, maintaining international market positions, and can reduce climate-policy-induced unemployment.

Keywords: Climate Policy, International Trade, Distortions, Carbon Leakage, Market Power

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1 Introduction

Substantial reductions in global greenhouse gas emissions seem to be necessary to address the problem of climate change. The costs of these reductions can be minimized by a globally coordinated policy. But, so far, only few countries have committed to notable emission reductions, and it seems unlikely that binding emission constraints will be accepted by the majority of emitters within the next years.

Despite this lack of global action, some governments pursue an active climate policy. For instance, the EU aims at reducing its greenhouse gas emissions by about 20% till 2020 and reduction targets have recently also been announced in the US. Such unilateral[1] policies are important, because they induce research in abatement technologies, which reduces abatement costs and thus helps to convince more countries to instate emission reduction measures. But governments that enact such unilateral policies are often subject to intense domestic pressure.

Three arguments are frequently used to question the value of a unilateral climate policy. First, such a policy is seen as ineffective, because costly emission constraints will drive emission-intensive industries to less active countries, so that national emission reductions will be partially compensated by emission increases in other countries (carbon leakage). Second, in the presence of labor market imperfections, national emission reductions can cause unemployment. Emission constraints will reduce the marginal productivity of labor, if these constraints are unilateral and thus not adequately reflected in international product prices. Under wage rigidities, this productivity reduction can induce unemployment. Finally, national industries can become less competitive, so that favorable trade positions can be lost. If a country has a strategic advantage on an international market, unilateral climate policy can reduce this advantage and thus be rather costly from a national perspective.

There is extensive literature that addresses these issues.[2] But while the main conclusion is that a global coordination of climate policy is important, only few studies investigate what should be done if international climate negotiations fail or become stalled for some time. Is it possible to reduce the negative side effects of unilateral climate policy by using specifically designed policy measures?

In principle, combating these side effects is simple. Supplementing climate policy with tariffs or export subsidies could mitigate the negative effects of unilateral action. However, by the WTO Agreement on Subsidies and Countervailing Measures, export subsidies are generally outlawed, while import tariffs on many goods categories are bound or even cut to zero by the agreements of the Uruguay Round, and national leeway for tariffs might be further reduced once the Doha Round is concluded. The legality of alternative trade measures such as border tax adjustments for energy inputs is disputed, and thus their applicability remains controversial and uncertain.

Therefore, the literature focuses on less direct measures. The most frequently discussed option is to differentiate climate policy between sectors that are open to international trade and those that are not. Such policy differentiation is reasonable from a national perspective, although it induces inefficiencies, (Hoel, 1996; Withagen et al., 2007).

However, policy differentiation is not a universally applicable solution. A substantial part of emissions is not directly caused by final goods sectors. Rather, it results from the production of intermediate goods, and many export industries are affected more by climate policy via increasing prices of these goods than via direct compliance costs. An important example is energy. In 2006 around 30% of the CO_2-equivalent greenhouse gas emissions of the EU-27 were caused by the energy industries (UNFCCC, 2006), and almost 40% of US CO_2-emissions were generated by electricity production (EIA, 2008a). A large fraction of this energy is used as an input in export industries. Policy differentiation is not feasible if sectors that differ with regard to their exposure to international competition do not directly cause emissions but rather contribute to a country's emissions by using emissions-intensive intermediate goods. It is not possible to differentiate an emission tax levied in an intermediate goods sector according to where the intermediate good is used in fin al goods production. Thus, the benefits of adjusting emission taxes to the exposure to international competition cannot be reaped.

But, as markets for important emission-intensive intermediate goods, such as electricity or transportation services, are often national, it is possible to intervene in these markets. For example, climate policy might lead to an increase in the price of electricity and thus to higher costs in final goods production, which can induce carbon leakage and unemployment as well as a loss of market power on international markets. To reduce these side effects, it could be reasonable from a national perspective to tax the emissions caused by electricity generation (thereby inducing abatement, such as the use of more efficient power plants, wind or solar energy) and to subsidize electricity to shield final goods production from increasing electricity prices (thereby reducing the negative side effects of unilateral climate policy).

Such a policy induces inefficiencies and alters the dynamic incentives of climate policy. But it could be a reasonable tool for a transitory climate policy until broad international agreements are reached.

The idea of this containment approach is similar to the policy differentiation of Hoel (1996) and Withagen et al. (2007) in that this approach also aims at reducing the burden of those sectors that are open to international trade. The concepts differ in that they apply to different industries. Policy differentiation is possible, if the sectors that are open to international trade directly cause substantial emissions, as is the case in the cement industry or the iron and steel industry. Our approach applies to settings, where the sectors that are open to trade cause emissions mostly by using energy-intensive inputs, as in manufacturing, parts of the chemical industry, or the service sector. Thus our containment approach is complementary to the policy differentiation concept. Furthermore, both approaches have different economic implications. Policy differentiation is costly, because it allocates abatement inefficiently among sectors. Containment does not alter the allocation of abatement but leads to an inefficient use of energy-intensive inputs. Thus the consequences for factor allocation in the general equilibrium differ substantially.

In this paper, we use a simple model of unilateral climate policy in a small open economy to investigate whether interventions in an intermediate goods market are a reasonable way to alleviate the side effects of unilateral climate policy. Our setup consists of a general equilibrium model of a three-sector economy. One sector produces an intermediate good and is environmentally regulated, and the two other sectors produce final goods with one sector being open to international trade and one sector producing solely for the home country's internal market. To separate the strategic decision of whether a country will commit to a unilateral policy from the question of how such a commitment should be implemented, we assume that the policy target is already fixed.

In this setup, we consider the above three arguments against unilateral climate policy and show that each of the negative side effects can be reduced by an intervention in the intermediate goods market. For each of these cases, we derive the optimal policy mix. Typically, it consists of an emission tax and a subsidy on the intermediate good.[3] Except for the case of maintaining market power, the optimality of intervening in the intermediate goods market is not due to strategic behavior.

In the following section, we briefly review the related literature. Then we set up our model. In Section 4, we derive the optimal policy and analyze how our approach relates to the concept of policy differentiation. Section 5 concludes the paper.

2 Review of the Literature

Our study relates to three distinct strands of literature. The first of these is the literature on optimal policies in the presence of distortions such as factor immobility, wage rigidity, or non-economic targets.

Bhagwati and Ramaswami (1963) have shown that if the distortion is domestic, that is, if, under laissez-faire, the domestic rates of substitution and transformation are not equal, the best policy is domestic intervention. However, if the domestic and the foreign rates of transformation differ, for example, due to monopoly power, the optimal intervention is a trade tariff or subsidy. Bhagwati and Srinivasan (1969) investigate the question of how to implement a given non-economic goal, such as a certain employment level or a minimum output of a given good, at the least possible social cost. The results of Bhagwati and Srinivasan (1969) relate intuitively to those of Bhagwati and Ramaswami (1963) and boil down to the principle that the optimal intervention takes place directly where the non-economic objective lies and does not include trade intervention. For example, to reach a given minimum domestic output level, the optimal policy is an output subsidy (and not an import tariff). A collection and unification of results on distortions, policy interventions and welfare can be found in Bhagwati (1971). Krishna and Panagariya (2000) add to the literature by clarifying some important issues of the theory of second-best interventions. In particular, they demonstrate that second-best policies crucially depend on whether the distortion takes the form of a restriction of choice variables or is a restriction on a first-order condition. In the former case, the first-order conditions of the first-best solution continue to characterize the optimum, and there is no justification for intervention in undistorted sectors.

The second line of research, which our paper relates to, is the climate policy literature. While game theoretic methods, in particular coalition theory, have been widely applied to study the formation and stability of international climate agreements,[4] some research has also been done on unilateral climate policy in the absence of a global framework.

Hoel (1996) and Withagen et al. (2007) examine the question as to whether emission regulation should be differentiated across sectors if a country pursues climate policy unilaterally. Both Hoel (1996) and Withagen et al. (2007) find that there is no reason for a differentiated emission policy as long as trade policy instruments such as tariffs are available. But in case trade policy is ruled out, a differentiated regulation is second-best. This result is due to carbon leakage in Hoel (1996) and due to terms-of-trade effects in Withagen et al. (2007). In the absence of both carbon leakage and terms-of-trade effects, a uniform climate policy is always optimal. Rauscher (1994) takes a positive rather than a normative approach and finds that strategic trade incentives, terms-of-trade arguments or political economy reasons might lead to sectoral differences in the stringency of emission policy.

Also, CGE modeling has been applied to analyze the effects of unilateral climate policies. Böhringer and Rutherford (2002) study sectorally differentiated tax regimes, and Dessus and O'Connor (2003) estimate ancillary benefits from unilateral climate policy in Chile. Carbone et al. (forthcoming) study a setting where countries set nationally optimal emission targets and can afterwards trade emission rights internationally. Surprisingly, substantial emissions reductions can be achieved in this way.

Finally, Copeland and Taylor (2005) explore a general equilibrium model with many countries and demonstrate that there might be negative carbon leakage; that is, unilateral emission cuts by some countries can lead to emission reductions by other countries. This somewhat surprising result is due to an income effect that counters the usual drivers of carbon leakage. Hence, the sign and magnitude of emission change in the rest of the world after a unilateral emission reduction by some countries is determined by a trade-off between free riding, substitution and income effects.

The third set of studies that our analysis is related to is the double dividend literature. A double dividend from environmental regulation arises if, independent of the reduction of environmental damage, a gain or a smaller loss in welfare is achieved by using the proceeds from environmental taxation to replace or reduce pre-existent distortionary taxes.[5] The weak double dividend hypothesis states that the welfare costs of environmental taxation is lower if such a "green tax reform" is carried out instead of returning tax revenue in a lump-sum fashion. If the green tax reform as a whole comes at zero or negative costs, a strong double dividend is reaped (Goulder, 1995). The theoretical soundness of the strong double dividend hypothesis has been widely criticized due to the tax-interaction effect, which works against the welfare-increasing revenue-recycling effect (Bovenberg and de Mooij, 1994; Parry, 1995; Bovenberg and Goulder, 1996). Through the tax-interaction effect, environmental taxes raise the welfare costs of distortionary income taxation by increasing prices and thus further lowering the already suboptimal labor supply. However, Schwartz and Repetto (2000) show that if the assumption of separable utility functions is dropped, improvement of environmental quality can increase labor supply partially or even entirely offsetting the tax-interaction effect. Various other aspects of environmental revenue recycling, such as distributional concerns (Mayeres and Proost, 2001) or the interplay of environmental taxes with trade taxes (Smulders, 2001) have been studied. However, all of these concepts of additional dividends rely on the assumption of pre-existing distortions. Hence, in the absence of distortions, no second dividend exists, and optimal revenue recycling consists of lump-sum transfers.

3 The Model

We consider a small open economy that consists of three sectors. One sector provides an intermediate good, like electricity or transportation services, that is used for production in two final goods sectors. One of the final goods is traded internationally, whereas the other is a domestic good. This vertical model structure where the product of the upstream industry is not traded internationally resembles the setup of Hamilton and Requate (2004), who study strategic environmental policy.

In our basic setup, all factors can move freely between sectors and all markets are perfectly competitive. There is international trade for the above mentioned final good with national and foreign products being perfect substitutes. Furthermore, the resources needed to produce the intermediate good (such as fossil fuels) are imported. All other markets are national.

Greenhouse gas emissions arise only in the intermediate goods sector, which is consequently the subject of environmental regulation. In industrialized countries, a large fraction of greenhouse gas emissions results from the production of intermediate goods like electricity generation and transportation services.[6] For instance, trucks, that are mainly used for commercial purposes, accounted for more than 40% of gasoline and more than 80% of diesel consumption in the USA in 2006 (EPA, 2008). The energy industries caused more than 25% of CO_2-equivalent greenhouse gas emissions of Annex I countries in 2006 (UNFCCC, 2006).[7] Thus emissions from intermediate goods production are indeed quantitatively important. Furthermore, as we show in Section 4.4, our main conclusions remain valid in more general settings.

We consider a unilateral climate policy where only the country under consideration implements a policy to reduce greenhouse gas emissions. For simplicity, we constrain our investigation to a regulation based on an emission tax. But our results can be easily transferred to tradable permit schemes or to standards. As already mentioned, the policy aims at implementing a fixed national emission target, such as the 20% target of the EU.

The emission tax leads to a higher price of the intermediate good (e.g., electricity) and thus to higher factor costs in final goods production. As the policy is unilaterally enacted, the prices on international markets do not increase likewise, implying that production is shifted to countries without climate policy. The purpose of our study is to investigate whether it is reasonable from a national perspective to counter this effect by accompanying measures. As WTO rules preclude tariffs or export subsidies, and the feasibility of border tax adjustments is uncertain, we consider an accompanying intervention in the intermediate goods market.[8]

We assume that production possibilities in the intermediate goods sector are represented by the following cost function.

$$c_I(q_I, a_I) = c_P(q_I) + q_I c_A(a_I), \tag{1}$$

where q_I denotes output, a_I is abatement, and $c_P, c_A : \mathbb{R}_+ \to \mathbb{R}_+$ are twice differentiable, strictly increasing cost functions with $c_P(0) = c_A(0) = 0$. Emissions are given by $e = q_I(\bar{\epsilon} - a_I)$. Thus $c_A(a_I)$ are the costs of reducing emissions per unit of production from their baseline level $\bar{\epsilon}$, whereas $c_P(q_I)$ are the production costs in the absence of abatement. We assume that c_A is a strictly convex function, whereas c_P might be linear (which implies constant returns to scale) or strictly convex (implying decreasing returns to scale).[9]

To keep the analysis tractable, we assume that these costs arise solely due to the use of imported factors, such as fossil fuels or machinery, and that the amount of labor employed in the production of the intermediate good is negligible on a national scale. In the examples given above, this is a reasonable assumption. Although electricity generation and transportation services account for a large part of the emissions of industrialized countries, the fraction of labor employed in these sectors is rather small.

We depict the production possibilities in the final goods sectors by production functions that depend on the quantity of the intermediate good and labor. The production functions are given by $f_{NT}(l_{NT}, q_{I,NT}) : \mathbb{R}^2_+ \to \mathbb{R}_+$, for the non-trading sector, and by $f_T(l_T, q_{I,T}) : \mathbb{R}^2_+ \to \mathbb{R}_+$, for the trading sector. The variables l_T, l_{NT} denote the labor inputs of the final goods sectors and $q_{I,T}, q_{I,NT}$ are the quantities of the intermediate good used there. We assume that the production functions exhibit constant returns to scale and are twice differentiable, strictly increasing in their arguments, and strictly concave. There is a fixed supply of labor $\bar{L}$, so that full employment implies

$$l_{NT} + l_T = \bar{L}. \tag{2}$$

The climate policy consists of an emission tax τ and a subsidy σ. The former is levied on the emissions of the intermediate goods sector, the latter is paid for the output of this sector. The aim of the policy is to reduce emissions to an exogenously given level $\tilde{e}$. We assume that the subsidy is not differentiated, that is, both final goods sectors benefit from it. This is likely to be suboptimal. But a differentiated subsidy would cause substantial problems in implementation and might be seen as a trade-distorting measure. Furthermore, if an undifferentiated subsidy is welfare increasing, the same also holds for an optimally differentiated subsidy.

We do not impose a budget constraint on the policy and do not account for inefficiencies caused by raising the necessary revenue to cover a potential gap between the expenditures for the subsidy and the revenue of the emission tax. In effect, this amounts to assuming that profits gained by the policy are spent for a lump-sum transfer to the households, whereas incurred losses are covered by a lump-sum tax. This assumption is for presentational simplicity only; it does not affect our main conclusions. As the policy induces a tax revenue, it is always possible to have a strictly positive subsidy. Thus in a budget-neutral policy, the optimal subsidy is either the subsidy that we derive in the following sections (if it can be financed) or the maximum subsidy that can be financed by the tax revenue.

The firms in the intermediate goods sector maximize their profit

$$\pi_I = (p_I + \sigma) q_I - c_P(q_I) - q_I c_A(a_I) - \tau q_I (\bar{\epsilon} - a_I), \tag{3}$$

leading to

$$p_I = c_P'(q_I^*) - \sigma + c_A(a_I^*) + \tau(\bar{\epsilon} - a_I^*), \tag{4}$$

$$\tau = c_A'(a_I^*). \tag{5}$$

Total emissions are given by $e = q_I^*(\bar{\epsilon} - a_I^*)$. With Eqs. (3)–(5), we get

$$\tau = c_A' \left(\bar{\epsilon} - \frac{\tilde{e}}{q_I^*} \right), \tag{6}$$

as the necessary tax τ to reduce emissions to $\tilde{e}$. Market clearing for the intermediate good implies that

$$q_I^* = q_{I,T}^* + q_{I,NT}^*, \tag{7}$$

where $q_{I,T}^*$ and $q_{I,NT}^*$ denote the profit-maximizing intermediate good demand of the final goods sectors.

The demand for the intermediate goods results from production in the final goods sectors. In the non-trading sector, profit maximization implies

$$p_I = p_{NT} \frac{\partial f_{NT}(l_{NT}, q_{I,NT})}{\partial q_{I,NT}}, \tag{8}$$

$$w = p_{NT} \frac{\partial f_{NT}(l_{NT}, q_{I,NT})}{\partial l_{NT}}, \tag{9}$$

where w denotes the wage and where p_{NT} is the price of the non-traded good. In the trading sector, we get

$$p_I = p_T \frac{\partial f_T(l_T, q_{I,T})}{\partial q_{I,T}}, \tag{10}$$

$$w = p_T \frac{\partial f_T(l_T, q_{I,T})}{\partial l_T}, \tag{11}$$

where p_T is the international price of the traded good. Instead of using a numeraire, we normalize prices so that $p_I + p_T + p_{NT} + w = 1$.

To measure the national welfare effects of the policy, we use the welfare of a representative consumer with a utility function $U(y_T, y_{NT})$ that depends on the consumption of the final goods. Consumption expenditures are restricted by national income

$$p_T y_T + p_{NT} y_{NT} \leq p_T f_T(l_T, q_{I,T}) + p_{NT} f_{NT}(l_{NT}, q_{I,NT}) - c_P(q_I) - q_I c_A(a_I). \tag{12}$$

To gain a reference point, we first consider a case in which there are no market imperfections, no strategic behavior, and in which carbon leakage effects are not taken into account. In this case, the optimal policy consists of an emission tax without a subsidy, as the following lemma shows.

Lemma 1. *In the case of a small open economy without market imperfections and without carbon leakage, the optimal policy to implement the emission target $\tilde{e}$ is the emission tax* (6) *without an accompanying measure (i.e., $\sigma^* = 0$).*

Proof. Maximizing $U(y_T, y_{NT})$ under the budget constraint (12), the market clearing constraints (2), (7), and $y_{NT} = f_{NT}(l_{NT}, q_{NT})$ with regard to y_T, y_{NT}, l_T, $q_{I,T}$, l_{NT}, $q_{I,NT}$, q_I and a_I yields first-order conditions that equal Eqs. (4)–(5), (8)–(11) for $\sigma = 0$. The necessary tax to meet the target $\tilde{e}$ follows from (6). □

4 Designing a Unilateral Climate Policy

As shown above, an optimal climate policy in an ideal world would consist only of a uniform emission tax or an emission trading scheme encompassing all emitting sectors; additional measures, such as subsidies, or a policy differentiation would only lead to distortions and reduce social welfare.

However, climate policy often has to be designed under less benign conditions. In the following sections, we inquire whether the problems of carbon leakage, induced unemployment, and loss of a favorable trade position can be reduced by a (partial) containment of the effects of climate policy to the intermediate goods sector.

4.1 Reducing Carbon Leakage

The causes and the magnitude of carbon leakage have been extensively discussed in the literature (see, for example, Hoel (1991); Golombek et al. (1995); or Copeland and Taylor (2005)). We investigate whether carbon leakage can be reduced by supplementing climate policy with additional policy measures and to what extent it is in the interest of a country to do so.

We assume that the home country is a small open economy in the sense that the country's exports or imports of the traded goods do not alter the prices on the international markets and do not change foreign demand. This is the case, if changes in domestic imports or exports are so small compared to the total trade volume that foreign production adjusts at constant marginal costs to the amount necessary for market clearing. Decreasing exports or increasing imports of the home country are thus fully compensated by an increase in foreign production. Of course, these assumptions are highly stylized and exclude several effects, especially income effects in the foreign countries. But they facilitate a clear separation of the intervention incentives attributable to carbon leakage from those related to terms-of-trade effects.

To depict carbon leakage, we assume that foreign firms use $\bar{q}_T$ units of the intermediate good to produce one unit of output of the traded good and that the intermediate good in these countries is produced without abatement; that is, the production of one unit of the intermediate good causes $\bar{\epsilon}$ units of emissions. With our above assumptions, global emissions E can thus be written as

$$E = (Y_T + y_T - f_T(l_T, q_{I,T}))\, \bar{q}_T \bar{\epsilon} + \tilde{e} + E^{NT,F}. \tag{13}$$

Here, Y_T denotes global demand for the traded goods and $E^{NT,F}$ are the foreign emissions due to production of the non-traded good.

To assess the costs caused by carbon leakage, we assume that the home country benefits from the decreasing global emissions via a reduction of national environmental damage, which we depict by a damage function $d(E)$. We assume that $d(E)$ is strictly increasing and convex in E for all $E \geq 0$ and that it is a differentiable function of $E \in \mathbb{R}_+$. As is standard, we subtract this damage from our measure of national welfare and assume that there are so many consumers that individual incentives to reduce the environmental damage by adjusting consumption are negligible.

With these settings, we get the following result.

Proposition 1. *Assume that*[10] $\left.\frac{\partial U(y_T, y_{NT})}{\partial y_T}\right|_{y_T^*, y_{NT}^*} > d'(E^*)\bar{q}_T\bar{\epsilon}$. *Then, from a national perspective, it is optimal to subsidize the intermediate good. The optimal subsidy is*

$$\sigma^* = \frac{d'(E^*)\, \bar{q}_T\, \bar{\epsilon}\, p_T}{\left.\frac{\partial U(y_T, y_{NT})}{\partial y_T}\right|_{y_T^*, y_{NT}^*} - d'(E^*)\, \bar{q}_T\, \bar{\epsilon}} \cdot \left.\frac{\partial f_T(l_T, q_{I,T})}{\partial q_{I,T}}\right|_{l_T^*, q_{I,T}^*}. \tag{14}$$

The necessary tax τ to constrain total national emissions to $\tilde{e}$ is given by Eq. (6).

Proof. See Appendix A.1. □

So, in the case of unilateral climate policy, it is optimal to subsidize the intermediate good. This is intuitive, because there are two market failures. First, the producers do not account for the costs of climate change, resulting in overproduction and a lack of abatement efforts. Second, the consumers do not consider these costs in their consumption decisions, so that an increase in domestic production costs due to policy-induced abatement efforts leads to a higher share of unregulated foreign producers in total production. An emission tax (or permit trading) can correct the first market failure. But if a unilateral climate policy is pursued in an open economy, the tax cannot correct the second market failure as well; consumers can avoid the increased costs of cleaner products by choosing goods produced in an unregulated country, resulting in carbon leakage. Thus a second intervention is necessary.

The optimal subsidy is easily interpretable. The numerator depicts the reduction in damage, if an additional unit of the traded good is exported, times the marginal productivity of the intermediate good in this sector. Thus it describes the benefit, in terms of reduced damage, of supplying an additional unit of the intermediate good to the traded-goods sector. The denominator equals the marginal social value of increased consumption normalized by the price of the traded good.[11]

Calculating the marginal reduction of the domestic excess supply (i.e., domestic production minus consumption) due to subsidizing the intermediate good shows that it is given by

$$\frac{\partial(x_T - y_T)}{\partial \sigma} = \frac{c_A(a_I) + c'_P(q_{I,T} + q_{I,NT})}{p_I c''_P(q_{I,T} + q_{I,NT})}. \tag{15}$$

The marginal reduction in national income B due to the subsidy is

$$\frac{\partial B}{\partial \sigma} = -\frac{\sigma - \tau(\bar{\epsilon} - a_I)}{c''_P(q_{I,T} + q_{I,NT})}. \tag{16}$$

With the optimal tax and subsidy, we get

$$d'(E^*)\,\bar{\epsilon}\,\bar{q}_T \frac{\partial(x_T - y_T)}{\partial \sigma} + \frac{\partial U(y_T, y_{NT})}{\partial y_T}\frac{\partial B}{\partial \sigma} = 0. \tag{17}$$

So the optimal subsidy balances its positive effects on the damage through less carbon leakage with its negative effect on utility via reduced national income. The reduction in national income stems from the inefficient factor allocation induced by the subsidy. Due to the subsidy, the final goods sectors calculate with a price of the intermediate good that does not reflect the marginal costs of supplying this good. Consequently, they use a socially suboptimal factor combination, which reduces national income.

The optimal subsidy does not directly depend on the production or the price of the non-traded good, because there are no distortions in this sector and, due to its seclusion from international trade, it is not an apt vehicle for reducing carbon leakage. However, the non-traded goods sector indirectly affects the optimal subsidy via the sectoral factor allocation.

Note that the optimality of intervening in the intermediate goods market is not attributable to strategic behavior of the home country, because strategic incentives cannot exist in the small open economy case considered here. Indeed, as Eq. (14) shows, the optimality of subsidizing the intermediate good is solely due to the damage caused by carbon leakage; for $d'(E) = 0$, that is, whenever carbon leakage does not result in higher damage, it is optimal not to intervene in the intermediate goods market.

The optimality of subsidizing the intermediate good is also not due to the national emission target being exogenous. Optimizing national welfare (including the national damage caused by national emissions and carbon leakage) with regard to (t, σ) without a fixed emission target leads to an optimal subsidy again given by Eq. (14) and $\tau = d'(E^*)p_T/((\partial U(y_T, y_{NT})/\partial y_T) - d'(E^*)\bar{q}_T\bar{\epsilon})$. In this case, the emission tax induces the intermediate goods sector to take the social damage caused by emissions into account and the market intervention is used to reduce the negative effect of carbon leakage.

The type of intervention studied here results in only a second-best outcome. A first-best result would be achievable by a tariff/export subsidy on the traded final good.[12] Such an intervention would increase domestic production of the traded good and decrease its domestic consumption without interfering with the optimal factor combination. However, such a policy is infeasible under WTO rules.

Finally, carbon leakage can also be caused by declining prices for fossil fuels induced by emission limits in the home country. As we consider a small open economy, this type of carbon leakage is not covered by our analysis. However, the containment strategy would also be helpful in this case, as it increases production of the intermediate good (and thus domestic fossil fuel consumption) compared to a single-instrument policy.

4.2 Market Distortions and Policy-Induced Unemployment

Another reason for using a policy mix are national market imperfections, such as price rigidities, factor immobility, or pre-existing market interventions. As unilateral climate policy is often criticized for being likely to lead to unemployment, we shall discuss a simple case of wage rigidities. The wage cannot adjust downward, so that a climate policy that reduces the marginal productivity of labor causes unemployment.

Initiated by Bhagwati and Ramaswami (1963), there is substantial literature that analyzes market interventions in an open economy with distortions, that is, with factor price rigidities and factor immobility. As discussed in Section 2, the optimal policy consists of an intervention (usually a subsidy) in the distorted market. In addition, there is extensive literature on designing environmental policy under pre-existing market interventions (see, for example, Bovenberg and de Mooij (1994) or Bovenberg and Goulder (1996)). Our setup deviates from the latter literature in that there are no pre-existing interventions; the economy is in an efficient equilibrium before the introduction of the climate policy. Our approach differs from the former literature in that we do not consider a change in the terms of trade that renders the distortions relevant but rather a change in national policy that reduces the supply of a factor (allowable emissions). Also, we do not assume factor immobility and use a model that differentiates between intermediate and final goods production.

In our case, an emission tax increases the price of the intermediate good, which in turn induces a decline in the marginal productivity of labor, resulting in unemployment. A subsidy on the intermediate good could be used to partially reverse this effect and thereby reduce the unemployment attributable to climate policy. The following proposition characterizes the optimal choice of (τ, σ).

Proposition 2. *Assume that there is a lower boundary $\bar{w}$ of the wage that equals the wage before the introduction of climate policy. Then the optimal policy (τ^*, σ^*) consists of the tax* (6) *and the following subsidy*

$$\sigma^* = \min\{\frac{l_T^*}{q_T^*}\bar{w}, c_A(a_I^*) + \tau^*(\bar{\epsilon} - a_I^*)\}. \tag{18}$$

Proof. See Appendix A.2. □

So, if climate policy induces unemployment due to wage rigidities, subsidizing the intermediate good is a feasible strategy to reduce unemployment. Two cases can emerge. First, it can be optimal to subsidize the intermediate good so that the price of this good is not affected by climate policy. This assures that climate policy induces no unemployment. This is optimal, if the traded good is labor intensive, that is, if l_T^*/q_T^* is large. Second, it can be optimal to reduce the effect of the emission tax on the price of the intermediate good somewhat but to keep this price higher than in the case without climate policy, which implies some unemployment. This is the case, if the traded-goods sector is not too labor intensive.

The optimal subsidy balances the gain of higher labor productivity, and thus less unemployment, with the costs of an inefficient combination of abatement and output reduction in the intermediate goods sector.

However, in contrast to the preceding and the following section, there is a better and feasible way to reduce the costs of unemployment induced by climate policy. This approach uses a subsidy on labor to bridge the gap between the wage and labor productivity at full employment. It is easily shown (see, e.g., Bhagwati and Srinivasan (1969)) that this is the best possible solution. Thus our argument is not that a subsidy on the intermediate good should be used to overcome climate-policy-induced unemployment.[13] Rather, our analysis suggests that if such a subsidy is used for other reasons, for example to reduce carbon leakage, there is the additional benefit that it reduces unemployment.

4.3 Maintaining Market Power

If the country committed to a reduction in greenhouse gas emissions is a large supplier or demander of the traded good, then changes of the net excess demand for that good will influence world prices. In the context of our model, this means that unilateral climate policy indirectly changes the terms of trade by causing a reallocation of factors between the non-traded-goods and the traded-goods sector and thereby leads to changes in production. In such a case, an additional intervention exploiting the country's monopoly (monopsony) power in trade can increase national income and thus welfare. If an optimal intervention had already been in place before the implementation of the emission target, this intervention would no longer be optimal and would need to be updated.

For analyzing the large country case, we need to slightly modify the model developed in Section 3 by altering the budget constraint (12) to

$$p_T(m_T)y_T + p_{NT}y_{NT} \leq p_T(m_T)f_T(l_T, q_{I,T}) + p_{NT}f_{NT}(l_{NT}, q_{I,NT}) - c_P(q_I) - q_I c_A(a_I). \quad (19)$$

where $m_T := x_T - y_T$ is the country's net excess demand for the traded good and where $p_T(m_T)$ is the international price in dependency on this excess demand.

We assume that although the country's export industry is large in the aggregate, each individual firm is small and thus acts under perfect competition. Hence, the incentives for adjusting the terms of trade are located on the government level not the firm level.

In principle, "optimization" of the terms of trade should take the form of direct trade measures such as export or import tariffs. Thus, in the presence of an emission limit and market power, the first-best policy is a combination of the optimum trade tariff and an emission tax. However, ruling out direct trade intervention, the government has an incentive to use an intervention in the intermediate goods sector as a secondary trade policy instrument. This is shown in the following proposition.

Proposition 3. *In case of a large country that has market power in the trading sector but cannot use direct trade intervention, it is optimal to intervene in the intermediate goods sector. The optimal intervention is given by*

$$\sigma^* = m_T^* \, p_T'(m_T^*) \cdot \left. \frac{\partial f_T(l_T, q_{I,T})}{\partial q_{I,T}} \right|_{l_T^*, q_{I,T}^*} \tag{20}$$

The necessary tax to constrain total national emissions to $\tilde{e}$ is given by Eq. (6).

Proof. See Appendix A.3. □

Proposition 3 shows that the sign of the optimal intervention in the intermediate goods sector depends on the sign of m_T, that is, on whether the country is a net importer or exporter of the final good. In our case, the budget constraint (19) implies that the country exports the traded good, as the resources for the production of the intermediate good are imported. Thus a tax on the intermediate good is optimal.

These results are intuitive in the light of the first-best trade policies. A classic result from trade theory says that the first-best policy for a country with monopoly power in trade is an export tax.[14] As the intervention on the intermediate goods sector is used as a substitute for such a direct measure, the optimal intervention analogously contracts supply.

Note that the optimal intervention does not directly depend on the emission target $\tilde{e}$. This is because the main driving force behind the intervention is its effect on the terms of trade. This effect is present in a large economy independent of an emission target. However, as the implementation of the emission target leads to a change in the price of the intermediate good and thus to factor reallocation, the magnitude of the optimal intervention is indirectly dependent on the emission target. Hence, setting an emission ceiling on the intermediate goods sector renders a previously optimal intervention suboptimal. In fact, the introduction of an emission tax will lead to a decrease in the size of the optimal intervention, as the emission tax is a substitute for the tax on the intermediate good.

The optimal intervention is neither equal nor equivalent to the optimal trade tariff, that is, to the inverse of the export demand supply elasticity,[15] due to two reasons. First, the output of the intermediate sector is an input in both final goods sectors. Hence, the intervention affects not only the production of the traded good as would be the case for a trade tax, but also changes output of the non-traded good. The reallocation of factors that leads to this change in output is inefficient, and thus comes at the cost of a decrease in national income. However, this loss is outweighed by an increase in national income due to the favorable change of the terms of trade. Second, a tax on a trading-sector input is an indirect measure as understood in the policy-targeting literature (see, e.g., Bhagwati and Ramaswami (1963), and Bhagwati and Srinivasan (1969)) and thus an inefficient instrument for the exploitation of monopoly power. Therefore, the optimal intervention goes beyond balancing the terms-of-trade effect with the quantity-of-trade effect; it also accounts for the inefficiencies that it produces as an indirect instrument.

Finally, this section has shown that it can be optimal not only to subsidize the intermediate good but also to tax it. Thus if carbon leakage, unemployment, and market power are simultaneously important in devising a unilateral climate policy, it is not obvious whether the intermediate good should be subsidized or taxed. However, some intervention in the intermediate goods market is optimal in most cases. Furthermore, we have only considered a simple case of a large open economy, where the good in question is always an export good. In many cases, large countries have monopsony power in important markets. In such cases, the optimal intervention is a subsidy on the intermediate good (cf. Eq. (20)), so that the direction of the intervention is clear, even if several intervention incentives apply simultaneously.

4.4 Differentiation or Containment?

Our analysis has shown that (partially) containing the effects of climate policy to the intermediate good sector is a reasonable strategy to combat negative side effects of a unilaterally enacted policy, such as carbon leakage or unemployment. A different approach to counter these effects is the policy differentiation analyzed in Hoel (1996) and Withagen et al. (2007). As we have argued in the introduction, the concepts of policy differentiation and containment are applicable in different settings; policy differentiation if trading and non-trading sectors cause emissions directly, containment if trading sectors contribute to overall emissions mainly by using emission-intensive intermediate goods as inputs in their production processes.

In most applications, there is a mixture of these cases: A part of emissions originates directly from final goods production and another part stems from the production of intermediate goods. Thus an important question arises: Which of these concepts should be used?

To analyze this question, we extend our model. We introduce a fourth sector that produces a final good, that directly causes emissions, and that is open to international trade. For simplicity, we assume that this sector is an export-only sector; that is, its product is not consumed within the country. Out of the three reasons for containment investigated in the preceding sections, we consider the case of carbon leakage, because carbon leakage is widely discussed in the literature and provides an important reason for policy differentiation. Thus we compare our concept of containment to a case of policy differentiation that is similar to the one discussed in Hoel (1996).

We model production possibilities in the fourth sector with a production function $f_R(l_R, e_R) : \mathbb{R}^2_+ \to \mathbb{R}_+$ that depends on the amount of labor l_R allocated to this sector and the emissions e_R of this sector. We assume that this production function exhibits constant returns to scale, is twice differentiable, strictly concave, and strictly increasing in both inputs. Again, we use the small-open-economy assumption; that is, the price p_R for the fourth sector's output is given and fixed. The constraint for labor supply becomes $l_{NT} + l_T + l_R = \bar{L}$, the budget constraint is

$$p_T y_T + p_{NT} y_{NT} \leq p_T f_T(l_T, q_{I,T}) + p_{NT} f_{NT}(l_{NT}, q_{I,NT}) + p_R f_R(l_R, e_R) - c_P(q_I) - q_I c_A(a_I), \tag{21}$$

and total emissions are given by

$$E = (Y_T + y_T - f_T(l_T, q_{I,T}))\, \bar{q}_T \bar{\epsilon} + (Y_R - f_R(l_R, e_R))\, \bar{\epsilon}_R + \tilde{e} + E^{NT,F}. \tag{22}$$

Here, Y_R denotes global demand for the fourth sector's good, and foreign production of this good causes $\bar{\epsilon}_R$ units of emission per unit of output. Note that we now have a double carbon leakage effect: In both the traded final goods sector and the fourth sector, climate policy can induce a shift of production to foreign countries and thus an increase in foreign emissions.

To investigate the relation between policy differentiation and containment, we introduce an emission tax τ_R levied on emissions in the fourth sector that can differ from the tax τ charged for emissions in the intermediate goods sector. Under these assumptions, profit maximization in the fourth sector leads to

$$w = p_R \frac{\partial f_R(l_R, e_R)}{\partial l_R}, \tag{23}$$

$$\tau_R = p_R \frac{\partial f_R(l_R, e_R)}{\partial e_R}. \tag{24}$$

The following proposition shows that, in this setup, it is optimal to use policy differentiation and containment simultaneously.

Proposition 4. *Assume that*[16] $\left.\frac{\partial U(y_T, y_{NT})}{\partial y_T}\right|_{y_T^*, y_{NT}^*} > d'(E^*)\bar{q}_T\bar{\epsilon}$. *Then, from a national perspective, it is optimal to subsidize the intermediate good and to differentiate the emission taxes.*

The optimal subsidy is given by

$$\sigma^* = \frac{d'(E^*)\, \bar{q}_T\, \bar{\epsilon}\, p_T}{\left.\frac{\partial U(y_T, y_{NT})}{\partial y_T}\right|_{y_T^*, y_{NT}^*} - d'(E^*)\, \bar{q}_T\, \bar{\epsilon}} \cdot \left.\frac{\partial f_T(l_T, q_{I,T})}{\partial q_{I,T}}\right|_{l_T^*, q_{I,T}^*}. \tag{25}$$

The optimal taxes to constrain total national emissions to $\tilde{e}$ *are*

$$\tau^* = c_A' \left(\bar{\epsilon} - \frac{\tilde{e} - e_R^*}{q_I^*}\right), \tag{26}$$

$$\tau_R^* = \tau^* \left(1 - \frac{d'(E^*)\, \bar{q}_T\, \bar{\epsilon}}{\left.\frac{\partial U(y_T, y_{NT})}{\partial y_T}\right|_{y_T^*, y_{NT}^*}}\right) + d'(E^*)\bar{\epsilon}_R \frac{p_R f_R(l_R^*, e_R^*)}{e_R^*} \cdot \frac{\frac{\bar{\epsilon}\bar{q}}{\bar{\epsilon}_R} - \frac{p_T}{p_R}}{\left.\frac{\partial U(y_T, y_{NT})}{\partial y_T}\right|_{y_T^*, y_{NT}^*}}. \tag{27}$$

Proof. See Appendix A.4. □

So, it is optimal to combine containment and policy differentiation. Emissions that are caused directly by an exporting sector should be taxed differently from emissions that originate from intermediate goods production. In addition, the intermediate good should be subsidized.

This is due to the double carbon leakage effect. If emissions were identically taxed and if there was no subsidy, the emission constraint would shift production to foreign countries and thereby increase foreign emissions. As discussed in Section 4.1, the subsidy on the intermediate good helps to reduce this negative effect. In addition, policy differentiation is useful for two reasons. First, emissions in the fourth sector are directly linked to exports (thus causing carbon leakage), whereas a part of the intermediate good is used in the production of the non-traded final good (where there is no carbon leakage). This provides an incentive to tax these emissions differently.[17] Second, the subsidy on the intermediate good redu ces the impact of the emission tax in this sector on carbon leakage, whereas no such attenuating measure exists in the fourth sector. Again, this renders policy differentiation reasonable.

Whether the optimal tax τ_R^* on emissions in the fourth sector is smaller or greater than that on emissions in the intermediate goods sector (τ^*) depends on the relative strength of the two carbon leakage effects (i.e., on $\bar{\epsilon}\,\bar{q}_T$ and $\bar{\epsilon}_R$), on the relative prices of the outputs, and on the emission intensity in the fourth sector. Analyzing (27) shows that we have $\tau_R < \tau$ if and only if $p_R < \tau^* \frac{e_R^*}{f_R(l_R^*, e_R^*)} + p_T \frac{\bar{\epsilon}_R}{\bar{\epsilon}\bar{q}_T}$. If the price of the fourth sector's output is small compared to the price of the traded final good, or if foreign production of the fourth sector's product causes much higher emissions per unit than foreign production of the traded final good, then the emissions in the fourth sector should be taxed less strongly than emissions in intermediate goods production.

Finally, it is instructive to compare this policy mix to the case where there is a fourth sector but where policy differentiation is not used. As can be easily shown, the optimal policy in the latter case consists of the tax (26) and the subsidy (25). Thus we get the same characterization of the optimal subsidy and the tax as in the case with policy differentiation,[18] only the tax is now applied to all emissions.

5 Conclusions

Theoretically, climate policy should be globally coordinated. But, in practice, such coordination is still lacking. In this paper, we have analyzed a unilateral climate policy that reduces the national costs of the policy while being compatible with international trade rules. This concept extends the main idea of policy differentiation to sectors where such differentiation is infeasible, such as intermediate goods production. It consists of (partially) containing the effects of climate policy to the production of an intermediate good that is emission intensive but not traded internationally. In practice, such a good could be electricity or transportation services, both of which account for a substantial fraction of national greenhouse gas emissions in most industrialized countries and serve mainly internal markets. The optimal containment strategy uses an emission tax to induce abatement efforts and a product subsidy (or tax) to control the effects on other sectors. We have shown that such a policy might help to counter three important objections against unilateral greenhouse gas reductions: by attenuating carbon leakage, allaying policy-induced unemployment, and helping to maintain a country's favorable position on international markets. Furthermore, we have shown that, in a setup with sectors that contribute directly and indirectly to aggregate emissions, it is optimal to combine the approaches of policy differentiation and containment.

Our analysis complements the literature on policy differentiation by considering the case of industries that are only indirectly accountable for greenhouse gas emissions due to using an emission-intensive intermediate good. In this quantitatively relevant case, a policy differentiation is not easily possible but an intervention in the intermediate goods market can help to constrain the effects of the climate policy to the intermediate goods sector. As in Hoel (1996) and Withagen et al. (2007), the costs of being a front runner in climate policy can be reduced by using a policy mix. Such a policy mix induces inefficiencies, because the emission reduction is not achieved by an optimal combination of abatement efforts and output reduction. But as output reductions are costly in the case of unilateral climate policy, due to carbon leakage or unemployment, this containment is reasonable from a national perspective.

An important objection to intervening in the intermediate good market is that this reduces the incentives for adjustments in final goods production. Subsidizing electricity reduces the incentives to use more energy-efficient production equipment and hampers adjustments in labor allocation, that is, a reallocation of labor from sectors that are more affected by climate policy to less affected sectors. However, it seems likely that climate policy will be coordinated among the major emitters at some time in the future.[19] Therefore, unilateral climate policy can be expected to be transitory. But once all major emitting countries commit to substantial emission reductions, international prices change and new adjustment processes are induced. As these later adjustments are likely to partially reverse adjustments that would seem necessary in the case of unilateral climate policy, it seems reasonable to defer substantial adjustments until a broad international consensus is reached. Furthermore, as containment uses a policy mix, it is easily possible to meet the same emission target while reducing the subsidy to the intermediate good over time. In this way, moderate adjustment incentives in the final goods sectors can be set.

A point that we have not considered in our analysis are the implications of containment on international negotiations. Our approach increases the effectiveness and decreases the costs of a national climate policy in the absence of a broad international agreement. Thus it is likely to induce more countries to adopt unilateral emission reductions and to lead to the setting of stricter targets. So in the short run, an increased reduction in global emissions can be expected. However, whether this will facilitate or complicate international negotiations is not clear. Trade economists have extensively analyzed the question whether unilateral trade liberalization and regional trade agreements are building blocks or stumbling blocks for global free trade.[20] The issue is still being actively studied and both views have numerous advocates. To our knowledge, the question whether unilateral or sub-global efforts to reduce greenhouse gas emissions constitute building blocks or stumbling blocks on the road towards a viable global climate agreement has not yet been investigated, and thus remains an open and interesting field for research.

Finally, as noted in the preceding sections, there are better ways (at least, in theory) to reduce the negative side effects of unilateral climate policy. We have chosen the intervention in an intermediate goods market, because it conforms to WTO rules, is easily implementable, and is able to address several side effects simultaneously. Of course, a policy that differentiates the subsidy among sectors according to their exposure to international competition would be better. But such a differentiated policy would be hard to implement and would, most likely, be challenged as being an inappropriate intervention in export and import markets. Furthermore, from a theoretical point of view, it is more important to show that the use of a simple instrument is welfare increasing. Naturally, this conclusion extends to more sophisticated instruments, as these grant more degrees of freedom.

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Notes

[1]To avoid awkward terminology, we refer to a national climate policy that is enacted outside the context of a global agreement including binding emission reductions for the major emitters as a "unilateral" policy. Of course, this term is not fully adequate, as some countries coordinate their policies, as in the EU.

[2]We briefly review this literature in the following section.

[3]In the case of maintaining market power, it can be optimal to tax the intermediate good.

[4]See Finus (2008) for a recent survey.

[5]This argument was developed as early as in the 1980s, see, e.g., Terkla (1984), and Lee and Misiolek (1986). For a survey see Schoeb (2003).

[6]Often, these "intermediate" goods are also used as final goods in consumption. For simplicity, we neglect this point. But it can be introduced into our model without substantial changes to our results.

[7]These intermediate goods are usually traded mostly on internal markets. For example, both the UK and the USA imported less than 1% of their total electricity consumption in 2007 (EIA, 2008b; BERR, 2008).

[8]Such an intervention conforms to WTO rules, as the policy subsidizes the domestic use of the intermediate good. Even if a fraction of the intermediate good is imported or exported, the intervention causes no distortion of international trade in the intermediate good, because the subsidy would not differentiate between imports and domestic production and would not be paid for exports.

[9]c_P could also be a strictly concave function, corresponding to increasing returns to scale. In this case, the second-order conditions need to be analyzed to assure that the optimal policy does indeed correspond to a welfare maximum. This will hold, as long as the curvature of c_P is not too large, that is, as long as the scale effect is not too strong.

[10]This condition assures that it is socially optimal to consume the traded good.

[11]The marginal damage is subtracted, because the policy results only in a second-best allocation. The price of the traded good is not influenced, so that consumers do not take the damage caused by increased consumption into account.

[12]The optimal subsidy would be $\sigma_T^* = \frac{d'(E^*)\bar{q}_T\bar{\epsilon}p_T}{\frac{\partial U(y_T,y_{NT})}{\partial y_T}\Big|_{y_T^*,y_{NT}^*} - d'(E^*)\bar{q}_T\bar{\epsilon}}$.

[13]There can be situations, where a subsidy on labor is not politically feasible. For instance, subsidizing labor can be costly, because the total labor force has to be subsidized. If the expenditures for the subsidy have to be covered by taxes that cause distortions, it can be better to use a subsidy on the intermediate good, which will often require much smaller expenditures.

[14]This argument originally goes back to Bickerdike (1906).

[15]Of course, the optimal intervention is not independent of the price elasticity of export demand. To see this, divide nominator and denominator of (20) by $p_T(m_T^*)$ to get $\sigma^* = p_T(m_T^*) \cdot \frac{\partial f_T(l_T,q_{I,T})}{\partial q_{I,T}}\Big|_{l_T^*,q_{I,T}^*} \frac{1}{\rho}$ where ρ corresponds to the elasticity. For $\rho \rightarrow -\infty$, the optimal intervention becomes zero, as the terms-of-trade effect of the intervention vanishes.

[16]Again, this condition assures that it is optimal to consume the traded good.

[17]This effect is comparable to differentiating an emission tax between sectors with differing exposure to international competition and thus with differing shifts of production to foreign countries in response to climate policy.

[18]Note that although the expressions are the same, the actual value of these policy instruments will differ, because these equations are evaluated at different equilibrium values of the endogenous variables.

[19]Otherwise, few countries would continue to pursue an active climate policy.

[20]For surveys, see Winters (1996) and Panagariya (1999).

A Proofs

A.1 Proof of Proposition 1

As the policy is a second-best policy, we calculate the subsidy σ^* by assuming that all endogenous variables (i.e., $q_{I,NT}$, $q_{I,T}$, l_{NT}, l_T, a_I, p_I, p_{NT}, w) as well as τ^* (as implied by Eq. (6)) are functions of this policy measure. We maximize the utility of the representative individual minus the damage caused by global emissions with regard to σ under the constraints that (i) total consumption expenditures do not exceed national income; that (ii) consumption of the non-traded good equals production of this good; and that (iii) total labor supply matches total labor demand. Using $\frac{\partial U(y_T,y_{NT})/\partial y_T}{\partial U(y_T,y_{NT})/\partial y_{NT}} = \frac{p_T}{p_{NT}}$, which characterizes the optimal relative consumption levels of the representative individual, the first-order condition can be written as

$$\frac{\partial U(y_T, y_{NT})}{\partial y_T}\left((\sigma-(\bar{\epsilon}-a_I)\tau^*)\left(\frac{\partial q_{I,T}}{\partial\sigma}+\frac{\partial q_{I,NT}}{\partial\sigma}\right)+(q_T+q_{NT})\tau^*\frac{\partial a_I}{\partial\sigma}-w\left(\frac{\partial l_{NT}}{\partial\sigma}+\frac{\partial l_T}{\partial\sigma}\right)\right)$$
$$= d'(E)\bar{\epsilon}\bar{q}_{I,T}\left((p_I+\sigma-(\bar{\epsilon}-a_I)\tau^*)\left(\frac{\partial q_{I,T}}{\partial\sigma}+\frac{\partial q_{I,NT}}{\partial\sigma}\right)+(q_T+q_{NT})\tau^*\frac{\partial a_I}{\partial\sigma}\right)-\nu p_T\left(\frac{\partial l_T}{\partial\sigma}+\frac{\partial l_{NT}}{\partial\sigma}\right) \tag{28}$$

where ν is the Lagrange coefficient of condition (iii) above.

To simplify this expression, we differentiate the characterization of firm behavior (Eqs. (4), (5), (6), (8),(10) and the zero-profit conditions for final goods sectors), the labor market constraint and our price normalization with respect to σ, taking the above mentioned endogenous variables as being functions of σ. After simplifying and exploiting constant returns to scale, we get the following expressions

$$\frac{\partial\tau^*}{\partial\sigma}=\frac{\tilde{e}c_A''}{\gamma(q_{I,T}+q_{I,NT})^2}, \qquad \frac{\partial a_I}{\partial\sigma}=\frac{1}{c_A''}\frac{\partial\tau^*}{\partial\sigma}, \tag{29}$$
$$\frac{\partial q_{I,T}}{\partial\sigma}=\frac{l_{NT}\,q_{I,T}}{(l_{NT}\,q_{I,T}-l_T\,q_{I,NT})\gamma}, \qquad \frac{\partial q_{I,NT}}{\partial\sigma}=\frac{l_T\,q_{I,NT}}{(l_T\,q_{I,NT}-l_{NT}\,q_{I,T})\gamma}, \tag{30}$$
$$\frac{\partial l_T}{\partial\sigma}=\frac{l_{NT}\,l_T}{(l_{NT}\,q_{I,T}-l_T\,q_{I,NT})\gamma}, \qquad \frac{\partial l_{NT}}{\partial\sigma}=\frac{l_{NT}\,l_T}{(l_T\,q_{I,NT}-l_{NT}\,q_{I,T})\gamma}, \tag{31}$$

with $\gamma := ((\bar{\epsilon}-a_I)\tilde{e}\,c_A''+(q_{I,T}+q_{I,NT})^2c_P'')/(q_{I,T}+q_{I,NT})^2$. Substituting Eqs. (29)-(31) into Eq. (28) yields Eq. (14). By our convexity assumptions, a solution of Eqs. (6) and (14) is necessarily a welfare maximum. $\square$

A.2 Proof of Proposition 2

We calculate the subsidy as above, but now the market clearing constraint for the labor market is only an inequality. The first order condition equals (28) with $d'(E) \equiv 0$ and $w = \bar{w}$. The Lagrange coefficient ν is zero, whenever the labor market constraint is not binding. Differentiating the characterization of firm behavior and the price normalization with regard to σ yields

$$\frac{\partial \tau^*}{\partial \sigma} = \frac{\tilde{e} c''_A}{\gamma (q_{I,T} + q_{I,NT})^2}, \qquad \frac{\partial a_I}{\partial \sigma} = \frac{1}{c''_A} \frac{\partial \tau^*}{\partial \sigma}, \tag{32}$$

$$\frac{\partial l_T}{\partial \sigma} = \left(\frac{1}{\gamma} - \frac{\partial q_{I,NT}}{\partial \sigma} \right) \frac{l_T}{q_{I,T}}, \qquad \frac{\partial l_{NT}}{\partial \sigma} = \frac{\partial q_{I,NT}}{\partial \sigma} \frac{l_{NT}}{q_{I,NT}}, \tag{33}$$

$$\frac{\partial q_{I,T}}{\partial \sigma} = \frac{1}{\gamma} - \frac{\partial q_{I,NT}}{\partial \sigma}, \tag{34}$$

with the same γ as above. To calculate $\partial q_{I,NT}/\partial \sigma$, we differentiate the characterization of the representative consumer's consumption bundle used in the preceding proof with respect to σ, substitute Eqs. (32)-(34) as well as the solution of the first order condition for σ with $\nu = 0$. This yields $\partial q_{I,NT}/\partial \sigma = 0$. Substituting all these conditions into the first order condition, shows that $\sigma^* = \bar{w}\, l_T/q_{I,T}$, if $\nu = 0$.

Whenever $\nu \neq 0$, the labor market constraint is binding. In this case, we get Eqs. (29)-(31), as in the preceding proof. Substituting these into the first-order condition (28) (with $d'(E) \equiv 0$), leads to $\sigma^* = 0$.

By assumption, $\bar{w}$ equals the marginal productivity of labor if there is no emission constraint. With any binding emission constraint and without the subsidy, the marginal productivity of labor is smaller than in this base case, because less of the intermediate good is used in final goods production and, by our assumptions on the technology, the intermediate good raises the productivity of labor. Thus we cannot have full employment without a subsidy. The largest subsidy that is compatible with $\nu = 0$, is $\sigma = c_A(a_I) + \tau^*(\bar{\epsilon} - a_I)$, as this subsidy reduces the price of the intermediate good to its level without climate policy. Consequently, the subsidy is either given by $\sigma^* = \bar{w}\, l_T/q_{I,T}$ or by this upper bound. $\square$

A.3 Proof of Proposition 3

We calculate the second-best intervention σ as above; only the price of the traded good is now a function of the exported amount of this good. The first-order condition is

$$\begin{aligned}&\frac{\partial U(y_T,y_{NT})}{\partial y_T}\frac{\partial y_T}{\partial \sigma}+\frac{1}{p_T}\left(\frac{\partial U(y_T,y_{NT})}{\partial y_T}\left(p_I\frac{\partial q_{I,NT}}{\partial \sigma}+w\frac{\partial l_{NT}}{\partial \sigma}\right)\right)\\&+\lambda\left(\left(\frac{\partial q_{I,T}}{\partial \sigma}+\frac{\partial q_{I,NT}}{\partial \sigma}\right)(\sigma+p_I-\tau^*(\bar{\epsilon}-a_I))+\tau^*\frac{\partial a_I}{\partial \sigma}(q_{I,T}+q_{I,NT})\right.\\&\left.\left(1+\frac{p_T'}{p_T}m_T\right)\left(\frac{\partial y_T}{\partial \sigma}p_T-\frac{\partial q_{I,T}}{\partial \sigma}p_I-\frac{\partial l_T}{\partial \sigma}w\right)\right)=\nu\left(\frac{\partial l_T}{\partial \sigma}+\frac{\partial l_{NT}}{\partial \sigma}\right),\end{aligned} \tag{35}$$

where λ and μ are the Lagrange coefficients of the representative consumer's budget constraint and of the labor market constraint. From analyzing the consumer's optimization problem, we get $\lambda = -(\partial U(y_T, y_{NT}/\partial y_T)/(p_T + p_T' m_T)$.

Again, we differentiate the characterization of firm behavior, the labor market constraint, Eq. (6), and the price normalization with respect to σ and get, with exploiting the constant returns to scale assumptions, Eqs. (29)-(31). Substituting these expressions and that for λ into Eq. (35) yields Eq. (20). □.

A.4 Proof of Proposition 4

Condition (26) for τ^* is the direct analogue to Eq. (6). We calculate the tax τ_R as well as the subsidy σ by assuming that all endogenous variables (i.e., $q_{I,NT}$, $q_{I,T}$, l_{NT}, l_T, l_R, e_R, a_I, p_I, p_{NT}, w) as well as he tax needed to implement the emission limit (τ^*) are functions of these policy measures and by optimizing the utility of the representative individual minus the damage caused by global emissions with regard to (σ, τ_R) under the constraints that (i) total consumption expenditures do not exceed national income; that (ii) consumption of the non-traded good equals production of this good; and that (iii) total labor supply matches total labor demand. The first-order conditions are

$$\begin{aligned}&\frac{1}{p_T}\frac{\partial U(y_T,y_{NT})}{\partial y_T}\left(\tau_R\frac{\partial e_R}{\partial \sigma}-\tau^*(q_{I,T}+q_{I,NT})\frac{\partial a_I}{\partial \sigma}+w\left(\frac{\partial l_R}{\partial \sigma}+\frac{\partial l_T}{\partial \sigma}+\frac{\partial l_{NT}}{\partial \sigma}\right)\right.\\&\left.-\left(\frac{\partial q_{I,T}}{\partial \sigma}+\frac{\partial q_{I,NT}}{\partial \sigma}\right)(\sigma-\tau^*(\bar{\epsilon}-a_I))\right)-\frac{d'(E)}{p_T}\left(\bar{\epsilon}\,\bar{q}_T\left(\tau_R\frac{\partial e_R}{\partial \sigma}+w\frac{\partial l_R}{\partial \sigma}-\tau^*(q_{I,NT}+q_{I,T})\frac{\partial a_I}{\partial \sigma}\right.\right.\\&\left.\left.-\left(\frac{\partial q_{I,T}}{\partial \sigma}+\frac{\partial q_{I,NT}}{\partial \sigma}\right)(\tau^*(\sigma-\bar{\epsilon}-a_I))\right)-\bar{\epsilon}_R\frac{p_T}{p_R}\left(\tau_R\frac{\partial e_R}{\partial \sigma}+w\frac{\partial l_R}{\partial \sigma}\right)\right)=\nu\left(\frac{\partial l_R}{\partial \sigma}+\frac{\partial l_T}{\partial \sigma}+\frac{\partial l_{NT}}{\partial \sigma}\right),\end{aligned} \tag{36}$$

$$
\begin{aligned}
&\frac{1}{p_T}\left(-\left(\frac{\partial U(y_T,y_{NT})}{\partial y_T}\left(-\frac{\partial e_R}{\partial \tau_R}\tau_R - w\left(\frac{\partial l_R}{\partial \tau_R}+\frac{\partial l_{NT}}{\partial \tau_R}+\frac{\partial l_T}{\partial \tau_R}\right)\right)+p_T\,\nu\right.\right. \qquad (37)\\
&\cdot\left(\frac{\partial l_R}{\partial \tau_R}+\frac{\partial l_{NT}}{\partial \tau_R}+\frac{\partial l_T}{\partial \tau_R}\right)+\left(\frac{\partial q_{I,NT}}{\partial \tau_R}+\frac{\partial q_{I,T}}{\partial \tau_R}\right)\left(\frac{\partial U(y_T,y_{NT})}{\partial y_T}\left(\sigma-\tau^*\,\bar{\epsilon}\right)\right)\\
&+\left(\frac{\partial U(y_T,y_{NT})}{\partial y_T}\right)\left(\left(\frac{\partial q_{I,NT}}{\partial \tau_R}+\frac{\partial q_{I,T}}{\partial \tau_R}\right)\tau^* a_I\ +\left(q_{I,NT}+q_{I,T}\right)\tau^*\frac{\partial a_I}{\partial \tau_R}\right)\Bigg)\\
&+\frac{d'(E)}{p_R}\left(\bar{\epsilon}_R\,p_T\left(\frac{\partial e_R}{\partial \tau_R}\tau_R+\frac{\partial l_R}{\partial \tau_R}w\right)+\bar{\epsilon}\,p_R\,\bar{q}_T\left(\frac{\partial a_I}{\partial \tau_R}\left(q_{I,NT}+q_{I,T}\right)\tau^*-\frac{\partial e_R}{\partial \tau_R}\tau_R\right.\right.\\
&\left.\left.-\frac{\partial l_R}{\partial \tau_R}w+\left(\frac{\partial q_{I,NT}}{\partial \tau_R}+\frac{\partial q_{I,NT}}{\partial \tau_R}\right)\left(\sigma+p_I+\tau^*(a_I-\bar{\epsilon})\right)\right)\right)=0
\end{aligned}
$$

where ν is the Lagrange coefficient of condition (iii) above.

To simplify these expressions, we use the same approach as above (with the characterization of firm behavior in the fourth sector being used in addition) and get Eqs. (29)-(31) with the exception of $\partial\tau^*/\partial\sigma$ which now equals $\frac{(\tilde{e}-e_R)c''_A}{\gamma(q_{I,T}+q_{I,NT})^2}$ and with γ now being defined as $\gamma := ((e_R-\bar{\epsilon})^2\,c''_A + (q_{I,T}+q_{I,NT})^3 c''_P)/(q_{I,T}+q_{I,NT})^3$. Furthermore, we get $\partial l_R/\partial\sigma = \partial e_R/\partial\sigma = 0$. For the derivatives with regard to τ_R, the following expressions can be gained in the same way.

$$
\frac{\partial a_I}{\partial \tau_R}=\frac{1}{c''_A}\cdot\frac{\partial \tau^*}{\partial \tau_R}, \qquad (38)
$$

$$
\frac{\partial q_{I,T}}{\partial \tau_R}=\frac{\partial \tau^*}{\partial \tau_R}\cdot\frac{\gamma_T\,q_{I,T}}{(l_{NT}\,q_{I,T}-l_T\,q_{I,NT})\gamma\,c''_P\,c''_A},\quad \frac{\partial q_{I,NT}}{\partial \tau_R}=\frac{\partial \tau^*}{\partial \tau_R}\cdot\frac{\gamma_{NT}\,q_{I,NT}}{(l_T\,q_{I,NT}-l_{NT}\,q_{I,T})\gamma\,c''_P\,c''_A}, \qquad (39)
$$

$$
\frac{\partial l_T}{\partial \tau_R}=\frac{\partial \tau^*}{\partial \tau_R}\cdot\frac{\gamma_T\,l_T}{(l_{NT}\,q_{I,T}-l_T\,q_{I,NT})\gamma\,c''_P\,c''_A},\qquad \frac{\partial l_{NT}}{\partial \tau_R}=\frac{\partial \tau^*}{\partial \tau_R}\cdot\frac{\gamma_{NT}\,l_{NT}}{(l_T\,q_{I,NT}-l_{NT}\,q_{I,T})\gamma\,c''_P\,c''_A}, \qquad (40)
$$

$$
\frac{\partial l_R}{\partial \tau_R}=\frac{\partial \tau^*}{\partial \tau_R}\cdot\frac{\gamma\,l_R\,(q_{I,T}+q_{I,NT})}{e_R\,c''_P\,c''_A},\qquad \frac{\partial e_R}{\partial \tau_R}=\frac{\partial \tau^*}{\partial \tau_R}\cdot\frac{\gamma\,(q_{I,T}+q_{I,NT})}{c''_P\,c''_A}. \qquad (41)
$$

Again, we have $\gamma := ((e_R-\bar{\epsilon})^2\,c''_A + (q_{I,T}+q_{I,NT})^3 c''_P)/(q_{I,T}+q_{I,NT})^3$ and we have defined $\gamma_T := (l_R q_{I,NT}(q_{I,T}+q_{I,NT})^2\gamma - e_R(\tilde{e}-e_R)l_{NT}c''_A)/(e_R(q_{I,T}+q_{I,NT}))$ and $\gamma_{NT} := (l_R q_{I,T}(q_{I,T}+q_{I,NT})^2\gamma - e_R(\tilde{e}-e_R)l_T c''_A)/(e_R(q_{I,T}+q_{I,NT}))$.

Substituting these expressions into Eqs. (36)-(37) yields conditions (25) and (27). □