Flattening the carbon extraction path:
Unilateral versus cooperative cost-effective action*

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DRAFT VERSION

Abstract.

Internalizing the global negative externality of carbon emissions requires flattening the extraction path of world fossil energy resources (= world carbon emissions). Policy instruments at the governments' disposal are sign-unconstrained emission taxes. Our focus is on the simple and pragmatic policy approach of preventing world emissions from exceeding some binding aggregate emission *ceiling* in the medium term. Such a *ceiling policy* can be carried out either in full cooperation of all (major) carbon emitting countries or by a sub-global climate coalition. Unilateral action has to cope with carbon leakage and high costs which makes a strong case for the choice of a policy that implements the ceiling in a cost-effective way. In a two-country two-period general equilibrium model with a non-renewable fossil-energy resource we compare the cooperative cost-effective ceiling policy with its unilateral counterpart. We show that with full cooperation there exists a cost-effective ceiling policy in which only first-period emissions are taxed at a rate that is uniform across countries. In contrast, the cost-effective ceiling policy of a sub-global climate coalition is characterized by emission regulation in both periods. That policy may consist *either* of positive tax rates in both periods *or* of negative tax rates (= subsidies) in both periods *or* of a positive rate in the first and a negative rate in the second period. The share of the total stock of energy resources owned by the sub-global climate coalition turns out to be a decisive determinant of the sign and size of unilateral cost-effective taxes.

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1 The problem

According to the standard economics of natural resources the intertemporal extraction path of non-renewable resources is too steep - too much is extracted too early - if resource consumption generates negative externalities. Scientific evidence strongly suggests that anthropogenic greenhouse gas emissions do create global climate change damage. As carbon dioxide is the most important greenhouse gas, internalizing those climate externalities requires curbing carbon emissions through reducing the use of fossil energy resources in the short and medium term[1]. Essentially, climate policy therefore requires flattening the intertemporal extraction path of fossil energy resources. Although the United Nations Framework Convention on Climate Change (UNFCCC 1992) does not explicitly refer to the resource economists' analytical approach to climate change, essentially it also calls for flattening the extraction path to achieve the ultimate objective of stabilizing "… greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

The economists' approach to determining the 'optimal flattening' of the extraction path would be a hybrid cost-benefit analysis which is, however, controversial both in science and politics as a guide to climate policy (Lave 1996, Ackerman 2004). A more pragmatic and operational approach backed by some scientific evidence consists in identifying the climate stabilization target with the goal to prevent the world mean temperature from exceeding 2^o Celsius above pre-industrial level. That goal has been endorsed by various governments as well as by the Council of the European Union (2005) and most recently also by the recent UN Conference of the Parties in Cancun. According to Meinshausen et al. (2009) the 2^o C temperature limit can be observed with reasonable probability, if the cumulated emissions until 2050 do not exceed some threshold quantity.[2] Essentially, that threshold is a global *ceiling* on emissions cumulating until 2050 referred to as 'carbon budget' by WBGU (2009) and Kalkuhl and Edenhofer (2010). In that pragmatic way the goal of climate stabilization is translated into the goal of preventing world total emissions from exceeding some ceiling in the medium term, say in 2050. With the realistic expectation that global laissez-faire emissions would be exceed that ceiling before 2050, meeting the ceiling requires an active climate policy which we denote a *ceiling policy*, for short.

In the present paper we focus on ceiling policies only without consideration of the climate externalities in the formal analysis. If an international climate agreement will be reached in the future at all, it will likely be based on that concept. Climate agreements may either encompass all (relevant) countries in the world which does not appear to be likely in view of the poor results of the international climate negotiations in recent years. Or it is only a subglobal coalition that strikes a climate agreement. When a global climate coalition carries out a ceiling policy it does so with all emissions (of all countries) under its control. In contrast, the unilateral ceiling policy of a subglobal climate coalition runs into the well-known problem of carbon leakage and its climate policy may even be self-defeating in case of excessive carbon leakage.

We will assume that there exist feasible ceiling policies for the subglobal climate coalition (which can safely be expected, if the coalition is not too small and the ceiling is not too tight). The focus is then on characterizing the set of feasible ceiling policies and on investigating properties of that particular feasible ceiling policy which achieves the predetermined ceiling at minimum cost for the subglobal climate coalition. For reference purposes

[1] In the present paper we disregard greenhouse gases other than carbon dioxide.

[2] Numerical estimates of that threshold are also suggested, e.g. 750 billion tons of CO_2 (WBGU 2009).

we will also compare the cost-effective ceiling policy of the subglobal coalition to the fully cooperative cost-effective ceiling policy.

This paper is related to the literature on carbon leakage which arises when one country's unilateral emission reduction policy increases the emissions in other countries. The so-called green paradox (Sinn 2008) is said to occur in the extreme case in which unilateral emission reductions increase rather than reduce aggregate world emissions, as compared to their level in the absence of that unilateral policy.[3] Hoel (1991), Bohm (1993), Golombek and Hoel (2004), Copeland and Taylor (2005), Di Maria and van der Werf (2005), Ishikawa and Kiyono (2006), Eichner and Pethig (2010), van der Ploeg and Withagen (2009) have analytically explored various channels and determinants of carbon leakage and/or the green paradox. Chakravorty et al. (2006) and Kalkuhl and Edenhofer (2010) employ the ceiling or carbon budget approach and characterize the cost-effective (cooperative) carbon budget policy in a one-country growth model. However, to our knowledge the extant literature does not consider subglobal climate coalitions that pursue a policy of limiting cumulative global emissions.

We will carry out the analysis in a stylized two-country two-period model similar to that in Eichner and Pethig (2010). Each country owns a share of the finite world stock of fossil fuels and the impact on ceiling policies of exogenous variations in the ownership shares will be investigated. Governments are assumed to have at their disposal emission taxes in the first and second period. The carbon ceiling is the sum of both countries' first-period emissions and is binding, i.e. is fixed below the countries' aggregate first-period emissions in the laissez-faire economy. First we analyze the fully cooperative cost-effective ceiling policy as a benchmark. It turns out that in this case cost effectiveness can be achieved via a tax on first-period emissions that is uniform across countries.[4] That policy is in the spirit of results from dynamic one-country models (Sinclair 1992, 1994, Sinn 2008) in which flattening the fossil-fuel extraction path requires high emission taxes early on and low or no taxes later.

Next we investigate the case of unilateral ceiling policies where the subglobal climate coalition is represented by one of the countries in our two-country model. In its effort to meet the ceiling in unilateral action that country's challenge is to restrict total first-period emissions via its domestic emission taxes which have an impact on the national emissions in both periods but do not determine the ceiling directly. Knowing that the government of the other country abstains from climate policy, the active country carries out its ceiling policy strategically in the sense that it takes into account the responses to its tax policy of all domestic and foreign consumers and firms. We show that there is a large set of feasible ceiling policies for one and the same predetermined ceiling and we classify these policies with respect to the sign and size of tax rates and with respect to the prices of fossil fuel and the consumption good corresponding to each policy. There are feasible policies with positive tax rates (emission taxes proper) in both periods, with negative tax rates (subsidies) in both periods, and there are feasible policies with a positive tax rate in the first and a negative tax rate in the second period. All these feasible ceiling policies differ, of course, with respect to the cost (= welfare loss) accruing to the country that undertakes the unilateral action. It is therefore not a trivial issue to identify the least-cost ceiling policy. We find

[3] There are various related concepts of green paradox, e.g. "… that anticipation of future reductions in demand for oil and other fossil fuels will drive the resource owners to bring forward their supply." (Gerlagh 2011).

[4] In our model, the cost-effective allocation turns out to be unique but can be implemented by various other combinations of (positive or negative) tax rates and fossil-fuel prices. For more details see Section 3 below.

that the sign and size of tax rates constituting the cost-effective unilateral ceiling policy depend on the distribution of ownership of the energy resource stock. The larger the resource stock of the country is that implements the ceiling, the larger is the shift of first and second-period tax rates from positive to negative rates.

The paper is organized as follows. Section 2 outlines the model. Section 3 investigates the properties of cooperative cost-effective ceiling policies. In Section 4 we characterize unilateral ceiling policies and focus on feasibility in the first part and on cost effectiveness in the second part of that section. Section 5 concludes.

2 The competitive two-country economy with carbon ceiling regulation

The structure of the model. In period $t = 1, 2$ country $i = A, B$ produces the amount x_{it}^s of the consumption good X, using fossil fuel e_{it} as an input.

$$x_{it}^s = X^i\left(e_{it}\right). \tag{1}$$

The representative consumer in country *i* derives utility, u_i, from consuming the amount x_{it} of good X in period *t.*

$$u_i = U^i\left(x_{i1}, x_{i2}\right). \tag{2}$$

Fossil fuel is a non-renewable resource. Its stock is $\overline{e}$ and country *i* owns the share α_i $\left(i = A, B\right)$ of that stock, where $\alpha_A = \left(1-\alpha_B\right) \in \left[\,0, 1\,\right]$.

Carbon emissions are generated in strict proportion to the amount of fossil fuel consumed. Hence with suitable definitions of units, e_{it} not only denotes fuel consumption but also carbon emission. The supply constraints for fossil fuel and for the consumption good X,

$$\overline{e} = e_{A1} + e_{B1} + e_{A2} + e_{B2}, \tag{3}$$

$$x_{At}^s + x_{Bt}^s = x_{At} + x_{Bt} \qquad t = 1, 2 \tag{4}$$

are obvious feasibility requirements. They turn into world market equilibrium conditions in the competitive economy studied below.

Regulation, competitive markets, and the agents' optimization problems. The principal target of regulation is to keep first-period emissions form exceeding an upper bound $\overline{e}_1 > 0$, which translates into the constraint

$$\overline{e}_1 = e_{A1} + e_{B1}. \tag{5}$$

We refer to $\overline{e}_1$ as (carbon) *ceiling*, for short. By ruling out the greater sign in the constraint (5) we restrict attention to ceilings $\overline{e}_1$ that are smaller than total first-period emissions in the absence of regulation. Consequently, In that case some fossil fuel consumption needs to be shifted from the first to the second period as compared with the laissez-faire scenario. That is exactly what the ceiling policy is about.

To the end of meeting the ceiling the governments of both countries have the option to regulate their domestic carbon emissions in either period. They can do so in two conceptually equivalent ways. Either they introduce national cap-and-trade schemes in one or both periods, where the emission cap of country *i* in period *t* is the politically chosen level of e_{it} and where π_{it} is the corresponding permit price. In that case, the independent policy variable is the cap e_{it} and the permit price adjusts as to equilibrate the permit market. Alternatively, we interpret π_{it} as the rate of an emission tax country *i* levies in period t. In that case, the tax is the independent policy variable the regulator chooses such that the resultant endogenous emissions e_{A1} and e_{B1} meet the ceiling $\overline{e}_1$. However, we will later consider scenarios with 'negative prices' π_{it} for some *i* and *t* which obviously cannot emerge as permit market equilibrium prices. That is why we stick to the tax policy interpretation with the obvious understanding that a negative tax is a subsidy.[5]

We will focus on two policy scenarios. In the first benchmark case both countries cooperate and coordinate their tax policies to implement the ceiling. In the second scenario country B refrains from taxing emissions altogether ($\pi_{B1} = \pi_{B2} \equiv 0$) while country A proceeds with meeting the ceiling in unilateral action.

The ceiling policy is embedded in a perfectly competitive two-country economy. In each period $t = 1, 2$ there exists a world market for the consumption good X with price p_{xt} and for fossil fuel with price p_{et}. We take the consumption good X in period 1 as numéraire, $p_{x1} = 1,$ and write $p_{x2} = p_x$ for convenience of notation.

Since there is no productive capital in our model, the market rate of interest is zero. The representative consumer of country *i* maximizes utility $U^i\left(x_{i1}, x_{i2}\right)$ subject to the budget constraint $x_{A1} + p_x x_{A2} = y_A$ and[6] $x_{B1} + p_x x_{B2} = y_B$ respectively, where the countries' incomes are

$$y_i := x_{i1}^s + p_x x_{i2}^s + p_e \triangle e_i \quad \text{with} \quad \triangle e_i := \alpha_i \overline{e} - e_{i1} - e_{i2}, \quad i = A, B. \tag{6}$$

Utility maximization yields

$$\frac{U^i_{x_{i2}}}{U^i_{x_{i1}}} = p_x. \tag{7}$$

An aggregate resource firm extracts the entire stock of fossil fuel, $\overline{e}$, over both periods. With zero extraction costs it maximizes present value profits $\sum_t p_{et} e_t$ where second-period profits is not discounted. That yields the simple Hotelling rule $p_{e1} = p_{e2} =: p_e$. As country *i* owns the share α_i of the resource stock, it claims the share α_i of the resource firm's profits.

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[5] To avoid complicated wording we refer to π_{it} as a tax rate except in specific results where we have explicitly established that $\pi_{it} < 0$.

[6] $\pi_1 e_{A1} + \pi_2 e_{A2}$ is the tax to be paid by the producer in country A. It is recycled to the consumer and is therefore implicitly contained in the definition of y_A.

In each country i an aggregate price-taking firm produces the consumption good X. Maximizing profits $\sum_t \left[p_{xt} X\left(e_{At}\right) - \left(p_{et} + \pi_t\right) e_{At} \right]$ and $\sum_t \left[p_{xt} X\left(e_{Bt}\right) - p_{et} e_{Bt} \right]$, respectively, gives us the first order conditions

$$X^i_{e_{i1}} = p_e + \pi_{i1}, \tag{8}$$

$$p_x X^i_{e_{i2}} = p_e + \pi_{i2}. \tag{9}$$

3 Cooperative cost-effective carbon ceiling regulation

Suppose now the countries A and B join forces to prevent world emissions from exceeding total first-period emissions $\overline{e}_1$. They aim at implementing the ceiling $\overline{e}_1$ at minimum total welfare cost $w_0 - w_1$, where $w = \omega_A u_A + \omega_B u_B$ is world welfare with agreed-upon welfare weights[7] $\omega_A, \omega_B \geq 0$ and where w_0 and w_1, respectively, is world welfare[8] before and after the cooperative ceiling policy. To characterize analytically the cooperative cost-effective ceiling policy, consider a social planner who maximizes world welfare $\sum_{i=A,B} \omega_i U^i\left(x_{i1}, x_{i2}\right)$ subject to (1) – (5). The corresponding Lagrangean reads

$$\begin{aligned} L = \sum_{i=A,B} \omega_i U^i\left(x_{i1}, x_{i2}\right) + \sum_{t=1,2} \left[X^A\left(e_{At}\right) + X^B\left(e_{Bt}\right) - x_{At} - x_{Bt} \right] + \\ + \lambda_e\left(\overline{e} - e_{A1} - e_{A2} - e_{B1} - e_{B2}\right) + \overline{\lambda}\left(\overline{e}_1 - e_{A1} - e_{B1}\right) \end{aligned} \tag{10}$$

The first-order conditions of solving (10) yield

$$\frac{U^i_{x_{i2}}}{U^i_{x_{i1}}} = \mu_{x2} \qquad \text{for } i = A, B, \tag{11}$$

$$X^i_{e_{i1}} = \mu_e + \overline{\mu}, \qquad \text{for } i = A, B, \tag{12}$$

$$\mu_{x2} X^i_{e_{i2}} = \mu_e. \qquad \text{for } i = A, B, \tag{13}$$

where $\mu_{x2} := \lambda_{x2} / \lambda_{x1}$, $\mu_e := \lambda_e / \lambda_{x1}$ and $\overline{\mu} := \overline{\lambda} / \lambda_{x1}$ are positive shadow prices in terms of first-period output X evaluated at the solution of (10). To make use of the preceding information about the efficient allocation in the standard procedure of decentralization by prices (and taxes) it is convenient to denote a cooperative tax policy as $\pi := \left(\pi_{A1}, \pi_{A2}, \pi_{B1}, \pi_{B2}\right)$ and define the set

$$\Pi := \left\{ \pi \in \mathbb{R}^4 \;\middle|\; \pi_{A1} = \pi_{B1}, \pi_{A2} = \pi_{B2}, \pi_{A1} = \overline{\mu} + \pi_{A2}, \pi_{A2} \in \left]-\infty, \mu_e\right] \right\}.$$

Proposition 1.

(i) The cooperative tax policy implements the ceiling $\overline{e}_1$ cost-effectively, if and only if $\pi := \left(\pi_{A1}, \pi_{A2}, \pi_{B1}, \pi_{B2}\right) \in \Pi$. In the associated competitive equilibrium the prices are

[7] The welfare weights can be interpreted as being fixed in a cost-sharing agreement which is taken as given.
[8] World welfare is calculated here before environmental damage is substracted.

$p_e = \mu_e - \pi_{A2}$ *and* $p_x = \mu_{x2}$*. Moreover, country A needs to make a suitable income transfer to country B whose sigh and size depends on* π_{A2}*, on* (ω_A, ω_B) *and on* (α_A, α_B)*.*

(ii) The equilibrium allocation is the same for all $\pi \in \Pi$ *and is characterized by*

$$\frac{X^A_{e_{A1}}}{X^B_{e_{B1}}} = \frac{X^A_{e_{A2}}}{X^B_{e_{B2}}} = 1, \quad \frac{X^A_{e_{A1}}}{X^A_{e_{A2}}} = \frac{X^B_{e_{B1}}}{X^B_{e_{B2}}} = \left(1 + \frac{\bar{\mu}}{\mu_e}\right) p_x, \qquad \textit{(production efficiency)} \qquad (14)$$

$$\frac{U^A_{x_{A2}}}{U^A_{x_{A1}}} = \frac{U^B_{x_{B2}}}{U^B_{x_{B1}}} = p_x, \qquad \textit{(consumption efficiency)} \qquad (15)$$

$$\frac{U^i_{x_{i2}}}{U^i_{x_{i1}}} - \frac{X^i_{e_{i1}}}{X^i_{e_{i2}}} = -\frac{\bar{\mu} p_x}{\mu_e} \quad \text{for } i = A, B. \qquad \textit{(intertemporal distortion)} \qquad (16)$$

It is easy to see that with the definitions $\pi \in \Pi$, $p_e = \mu_e - \pi_{A2}$ and $p_x = \mu_{x2}$ the conditions (11), (12) and (13) coincide with the conditions (7), (8) and (9). This is true for all $\pi \in \Pi$ which implies, in particular, that the allocation of inputs and outputs is the same for all $\pi \in \Pi$. Hence world income is uniquely determined. In the social planner's solution the market clearing conditions (4) are satisfied. Therefore, there exist incomes, say y^*_A, y^*_B, satisfying $y^*_A + y^*_B = x^s_1 + p_x x^s_2$ such that the consumption bundles (x_{i1}, x_{i2}) in the solution of (10) maximize utility $U^i(\cdot)$ subject to the income y^*_i. However, since p_e is not invariant with respect to the choice of $\pi \in \Pi$, y_i from (6) depends on π. We account for that relationship by writing $y_i = y_i(\pi)$ and observe that $y_i(\pi) \neq y^*_i$, in general. To assign the incomes y^*_A and y^*_B to the countries A and B, respectively, we define $T(\pi) := y_A(\pi) - y^*_A$ and let country A transfer the (positive or non-positive) amount $T(\pi)$ of its income $y_A(\pi)$ to country B.

An interesting feature of Proposition 1 is that although we deal with multiple equilibriums and multiple cost-effective ceiling policies in Proposition 1(i), those equilibriums are related in very special ways. The price p_x and the entire equilibrium allocation (of inputs, outputs and quantities of good X consumed) are the same in all equilibriums of Proposition 1. In contrast, the fossil-fuel price $p_e = \mu_e - \pi_{A2}$ depends on the policy $\pi \in \Pi$ chosen. Note, however, that the factor prices relevant for the firms producing good X are $p_e + \pi_{A1}$ in the first and $p_e + \pi_{A2}$ in the second period. In both countries these prices are the same for all $\pi \in \Pi$ which follows from the definition of the set Π. For all $\pi \in \Pi$ it is true that

- in each period the tax rates are uniform across countries[9] and
- the tax rate in period 1 is higher than in period 2 by the positive constant $\bar{\lambda}$.[10]

[9] Rather than levying uniform national taxes per period, one could also introduce a uniform world-wide tax in each period and use the proceeds for meeting burden-sharing requirements.

[10] That feature is analogous to the finding of Sinn (2008) and others in one-country growth models that flattening the extraction path requires levying high taxes early on and lower taxes later.

In other words, as long as those relations between tax rates are maintained, the level of taxes can be shifted up and down without affecting the levels of inputs and outputs because those tax shifts are exactly neutralized by shifts in opposite direction of the fossil fuel price p_e. Consequently, three subsets of the set Π can be distinguished. Both countries either

(i) leave first-period emissions unregulated and subsidize second-period emissions or

(ii) tax or subsidize emissions in both periods with first-period tax rates being higher than second-period tax rates, or

(iii) leave second-period emissions unregulated and tax first-period emissions only.

Although these policy options are technically equivalent one may prefer simple approaches ((i) and (iii)) over the hybrid policy of type (ii) and/or one may want to avoid (incredible?) commitments to regulation in the far future which would rule out the policies (i) and (ii). Under both selection criteria the policy option would perform best.

As the ceiling $\bar{e}_1$ is strictly binding by assumption, its implementation clearly requires distorting the allocation of the competitive equilibrium which prevails in the absence of regulation. Essentially, choosing the cost-effective cooperative policy means keeping the distortions at a minimum which accompany the move from laissez-faire to ceiling policy. Proposition 1(ii) establishes that cost effectiveness requires a policy such that

(i) the rations of intra-period marginal productivities of good X are the same across countries and that goes for the inter-period ratios as well (equation (14));

(ii) the marginal willingness-to-pay for consumption in period 2 (in terms of first-period good X) is the same across countries (equation (15))

(iii) the marginal willingness-to-pay for consumption in period 2 is smaller than the marginal cost of producing good X in period 2 (equations (16)).

While the conditions (i) and (ii) are (partial) efficiency requirements that are also satisfied in the laissez-faire economy, the condition (iii) specifies the allocative distortion which comes in the form of a wedge driven between the marginal willingness-to-pay for and the marginal cost of good X in period 2.[11] It is obvious from (16) that the equality of willingness-to-pay and cost would be achieved if $\bar{\mu} = 0$, i.e. if the ceiling $\bar{e}_1$ would not be or would only be weakly binding.

4 Unilateral carbon ceiling regulation

In the present section we assume that the government of country B is not cooperative and that there exist feasible strategies for country A to implement $\bar{e}_1$ unilaterally.[12] In its effort to meet the ceiling $\bar{e}_1$ in unilateral action country A's challenge is to restrict total first-period emissions to $\bar{e}_1$ via its tax rates (π_{A1}, π_{A2}) which have an impact on the national emissions e_{A1} and e_{A2} but do not determine the ceiling directly. Knowing that country B

[11] Note that according to (16) the wedge is the same across countries. That feature keeps the distortion small and will not carry over to the case of unilateral ceiling policy to be studied later.

[12] For more details see Section 4.1 below.

abstains from any (climate) policy country A needs to take into considerations country B's responses to its tax policy.

Unfortunately, informative results cannot be derived in the model used so far with general production functions X^i and utility functions U^i. To make progress we will reduce complexity in the remainder of the paper by assuming that the functions X^i and U^i are the same for both countries and that they take on the parametric forms

$$x_{it}^s = X^i\left(e_{it}\right) = ae_{it} - \frac{b}{2}e_{it}^2, \qquad a,b>0,\ i = A, B,\ t = 1, 2, \tag{17}$$

$$u_i = U^i\left(x_{i1}, x_{i2}\right) = x_{i1}^{\gamma} x_{i2}^{1-\gamma}, \qquad \gamma \in \left]0,1\right[\quad i = A, B. \tag{18}$$

As a consequence, (3), (5), (17) and the equivalent of (8) and (9) yield the fuel demand functions

$$e_{A1} = \frac{a}{b} - \frac{p_e}{b} - \pi_1, \qquad e_{A2} = \frac{a}{b} - \frac{p_e}{bp_x} - \pi_2, \qquad \text{with } \pi_1 := \frac{\pi_{A1}}{b} \text{ and } \pi_2 := \frac{\pi_{A2}}{bp_x} \tag{19}$$

$$e_{B1} = -\left(\overline{e}_1 - e_{A1}\right) = \frac{a}{b} - \frac{p_e}{b}, \qquad e_{B2} = -\left(\overline{e}_2 - e_{A2}\right) = \frac{a}{b} - \frac{p_e}{bp_x}. \tag{20}$$

We drop the 'original' emission tax rates π_{A1} and π_{A2} in favor of the modified tax rates π_1 and π_2 throughout the rest of the paper. We do so not only for convenience of notation but also because of the appealing implication $\pi_t = e_{Bt} - e_{At}$ which shows that π_t is a direct measure of the (intra-period) production distortion in period *t*.

The commodity demand functions

$$x_{i1} = \gamma y_i \quad \text{and} \quad x_{i2} = \frac{\left(1-\gamma\right) y_i}{p_x} \quad \text{for } i = A, B. \tag{21}$$

follow from (6), (7) and (18), after some rearrangement of terms. We conclude that under the functional forms (17) and (18) the competitive equilibriums with unilateral ceiling policy are fully characterized by the 12 equations (4), (6), (19), (20) and (21) which contain the 12 variables[13] $e_{A1}, e_{A2}, p_e, p_x, x_{A1}, x_{A2}, x_{B1}, x_{B2}, y_A, y_B, \pi_1$ and π_2. According to Walras Law, one of the market clearing conditions in (4) is already implied by all other equations. Thus we are left with 11 equations for 12 variables which means in economic terms that for any predetermined ceiling (not too stringent) country A has the choice among a variety of ceiling policies. The existence of multiple ceiling policies is, of course, a precondition for both the possibility and need to select a cost-effective policy.

4.1 Characterization of feasible unilateral ceiling policies

To prepare for the analysis of cost-effective unilateral ceiling policies, it is useful to explore first the properties of unilateral feasible ceiling policies. As shown in the preceding section we have a degree of freedom in specifying unilateral ceiling policies and we will take advantage of it by investigating the properties of the set of feasible ceiling policies

[13] The outputs x_{it}^s are already eliminated via (17) and the inputs e_{B1} and e_{B2} via (3) and (5).

generated by alternative 'fixed' levels of e_{A1}.[14] Some limits of feasibility are obvious. In particular, a necessary condition of a ceiling policy exhibiting $e_{A1} = 0$ clearly is that p_e be equal to the (low) price $\breve{p}_e := a - b\overline{e}_1$. $p_e < \breve{p}_e$ is incompatible with ceiling policies because e_{B1} would then exceed $\overline{e}_1$. Also, $e_{A1} > \overline{e}_1$ is no feasible choice either. The extreme case $e_{A1} = \overline{e}_1$ requires p_e to be greater than or equal to the choke price $p_e = a$. To keep focused we refrain from specifying feasibility conditions in detail. It is clear that country A can implement in unilateral action those ceilings that require only small reductions of the first-period emissions prevailing in the laissez-faire economy. The more stringent the ceiling is and the 'smaller' country A is relative to country B, the smaller will be the set of feasible unilateral ceiling policies. We will disregard those 'feasibility barriers' and proceed taking $E = \left[\,0, \overline{e}_1\right]$ as the domain of inputs e_{A1} for which a ceiling policy is feasible.

It is convenient to introduce the following additional notation. Define as $e_{A1}(\pi_2 = 0)$ the value of e_{A1} associated with the ceiling policy which exhibits $\pi_2 = 0$ and consider the following three subsets of the set E:

$$E_\ell := \left\{ e_{A1} \middle| 0 \le e_{A1} < e_{A1}(\pi_2 = 0) \right\}, \quad E_m := \left]\, e_{A1}(\pi_2 = 0), \overline{e}_1 / 2 \right[\quad \text{and} \quad E_h := \left\{ e_{A1} \middle| e_{A1} \ge \overline{e}_1 / 2 \right\}.$$

Note that the sets E_ℓ, $\{e_{A1}(\pi_2 = 0)\}$, E_m, $\{\overline{e}_1/2\}$ and E_h form a partition of E, if and only if $e_{A1}(\pi_2 = 0) \le \overline{e}_1 / 2$. We will demonstrate below that this condition is satisfied and that the partition is useful, indeed, for characterizing the set of feasible ceiling policies. With this notation we summarize the analytical properties of feasible ceiling policies in

Proposition 2. *Suppose the ceiling satisfies $\overline{e}_1 \le e_1^0$, where e_1^0 are total first-period emissions in the laissez-faire economy.*

(i) $$E_m \begin{Bmatrix} \ne \\ = \end{Bmatrix} \varnothing \;\Leftrightarrow\; e_{A1}(\pi_2 = 0) \begin{Bmatrix} < \\ = \end{Bmatrix} \frac{\overline{e}_1}{2} \;\Leftrightarrow\; \overline{e}_1 \begin{Bmatrix} < \\ = \end{Bmatrix} e_1^0.$$

(ii) Suppose that $\overline{e}_1 < e_1^0$. Over the interval $\left[\,0, e_{A1}(\pi_2 = 0)\,\right] \subset E$ of feasible policies the prices p_e and p_x are lower than their counterparts p_e^0 and p_x^0 in the laissez-faire economy.

(iii) Over the entire domain E of feasible policies, e_{A2} and p_e are strictly increasing in e_{A1}. Over the interval $\left[\,0, \overline{e}_1 / 2\,\right] \subset E$ of feasible policies, p_x is strictly increasing in e_{A1} but p_x is not monotone in e_{A1} on the sub-domain E_h.

(iv) Over the entire domain E of feasible policies, π_1 and π_2 are strictly decreasing in e_{A1} and the ceiling policy (π_1, π_2) is characterized by

(a) $\pi_1 > 0, \pi_2 > 0$, *if* $e_{A1} \in E_\ell$,

(b) $\pi_1 > 0$, $\pi_2 = 0$, *if* $e_{A1} = e_{A1}(\pi_2 = 0)$,

[14] Technically speaking, one could have taken as exogenous any other variable.

(c) $\pi_1 > 0 > \pi_2$, if $e_{A1} \in E_m$,

(d) $\pi_1 = 0$, $\pi_2 < 0$, if $e_{A1} = e_{A1}(\pi_1 = 0) = \overline{e}_1 / 2$,

(e) $\pi_1 < 0, \pi_2 < 0$ if $e_{A1} \in E_h$.

Some comments on Proposition 2 are in order.

Proposition 2(i) confirms that for binding ceilings there is an intermediate non-empty subset E_m of inputs e_{A1} on which feasible policies consist of a first-period tax and a second-period subsidy as shown in Prop. 2(iv)(c). Although the limiting case $\overline{e}_1 = e_1^0$ does not qualify as a climate policy, it will contribute to understanding the rationale of cost-effective policies below.

Proposition 2(ii) compares the prices p_e and p_x in ceiling policies with their counterparts in the laissez-faire economy. For all e_{A1} in the subdomain $\left[0, e_{A1}(\pi_2 = 0)\right] \subset E$ the results are as expected: The fossil fuel price declines under policies reducing the world demand for fossil fuel and the price for second-period consumption shrinks as well (which is equivalent to a price hike for first-period consumption because the latter is taken as numéraire). Note, however, that the interval $\left[0, e_{A1}(\pi_2 = 0)\right]$ is rather small because $e_{A1}(\pi_2 = 0) < \overline{e}_1 / 2$ and that ceiling policies on that interval do not involve subsidies. As established in Proposition 2(iii), p_e and p_x are increasing in e_{A1} (which holds for p_x up to some (high) level of e_{A1}). It is therefore well possible that there are $e_{A1} > e_{A1}(\pi_2 = 0)$ for which the price p_e and/or p_x are greater than their laissez-faire counterparts.

It is also a remarkable feature of feasible policies that e_{A2} is increasing in e_{A1}. To see the implication, take as a point of departure a ceiling policy for the lowest possible level of e_{A1} in which country A exports fossil fuel. As country A's resource stock $\alpha_A \overline{e}$ is given country A's exports of fossil fuel shrink and with successive parametric increases in e_{A1} such that the exports eventually turn into imports. Alternatively, if country A has imported fossil fuel initially (e.g. in the case $\alpha_A = 0$) its fossil fuel imports would expand. All these shifts are accompanied by rising prices of fossil fuel such that country A's export revenues shrink or its import bill rises.

Figure 1: Classification of feasible unilateral ceiling policies

Proposition 2(iv) does not only establish that the tax rates π_1 and π_2 are both strictly decreasing in e_{A1} but it also allows to determine the switches of these fiscal instruments from taxes proper to subsidies. That information of Proposition 2(iv) is illustrated in Figure 1 for the case $\overline{e}_1 < e_1^0$. The tax/subsidy switching points define the partition E_ℓ, $\left\{e_{A1}(\pi_2 = 0)\right\}$, E_m, $\left\{\overline{e}_1 / 2\right\}$ and E_h of the set of feasible policies, E. At low levels of e_{A1}, i.e. for $e_{A1} \in E_\ell$, the ceiling policy works via emission taxes proper, $\pi_1 > 0, \pi_2 > 0$; at intermediate levels of e_{A1}, i.e. for $e_{A1} \in E_m$, we need a first-period tax, $\pi_1 > 0$, but a second-period subsidy, $\pi_2 < 0$; at high levels of e_{A1}, i.e. for $e_{A1} \in E_h$, the ceiling policy works via emission subsidies, $\pi_1 < 0, \pi_2 < 0$. In the limiting case $\overline{e}_1 = e_1^0$ Figure 1 needs to be modified because the points $e_{A1}(\pi_1 = 0)$ and $e_{A1}(\pi_2 = 0) = \overline{e}_1 / 2$ on the abscissa of Figure 1 collapse into the point $e_{A1}(\pi_1 = 0) = e_{A1}(\pi_2 = 0) = \overline{e}_1 / 2$. As a consequence, there are no feasible ceiling policies $(\pi_1 > 0, \pi_2 < 0)$ anymore.

Recall that in Proposition 1(ii) we have characterized the distortions generated by the cooperative ceiling policy. Interestingly, consumption efficiency (equation (15)) carries over to the unilateral policy, but the production inefficiencies are more severe because now the ratios of marginal productivities differ intra- and intertemporally such that neither the equations (14) nor (16) are satisfied anymore.

The specification of feasible unilateral ceiling policies presented here certainly is an interesting piece of information in its own right. However, since country A's welfare - and cost of climate policy - varies with the policy chosen from the set of feasible ceiling policies, it is also of great interest to know which of those policies is country A's welfare maximizing – or cost-effective – policy.

4.2 Cost-effective unilateral ceiling policies

Consider a government of country A who knows that for each $e_{A1} \in E$ there is a policy (π_1, π_2) implementing the predetermined ceiling $\overline{e}_1 \leq e_1^0$. It also knows that the government of country B refrains from climate policy and it acts strategically in the sense that it takes into account the impact of its own policy on the domestic and foreign demands for fossil fuel and the consumption good X. If the ceiling policy related to some $e_{A1} \in E$ is carried out, the representative consumer of country A attains the utility

$$u_A(e_{A1}) = \left[x_{A1}(e_{A1})\right]^{\gamma} \cdot \left[x_{A2}(e_{A1})\right]^{1-\gamma}, \tag{22}$$

where we use here, temporarily only, the notation $x_{A1}(e_{A1})$ and $x_{A2}(e_{A1})$ to indicate that the levels of consumption x_{A1} and x_{A2} in (22) are ultimately determined by e_{A1} in the competitive equilibrium corresponding to the ceiling policy with $e_{A1} \in E$. Our subsequent analysis is based on the assumption that the utility (22) is single-peaked in e_{A1}.[15]

Invoking (21) we rewrite (22) as $u_A(e_{A1}) = \gamma^{\gamma}(1-\gamma)^{1-\gamma} p_x(e_{A1})^{\gamma-1} y_A(e_{A1})$ which yields, in turn,

$$\frac{du_A}{de_{A1}} = \frac{u_A}{y_A} \cdot \frac{dy_A}{de_{A1}} - (1-\gamma)\frac{u_A}{p_x} \cdot \frac{dp_x}{de_{A1}}, \tag{23}$$

where[16]

[15] Our strong conjecture is that single-peakedness holds unconditionally but we have not been able to establish that analytically because several terms with opposite signs are involved.
[16] For the derivation of (24) and (25) see the proof of Proposition 2(iii).

$$\frac{dy_A}{de_{A1}} = \frac{b(\pi_1 + \gamma \vartriangle e_A)}{\gamma} - x_{B2}^s \frac{dp_x}{de_{A1}}, \tag{24}$$

$$\frac{dp_x}{de_{A1}} = \frac{bp_x(\pi_1 - \overline{\gamma}\pi_2)}{\overline{\gamma}(p_x x_2^s - p_e \pi_2)} = \frac{bp_x(\pi_1 - \overline{\gamma}\pi_2)}{x_1^s - \overline{\gamma}\, p_e \pi_2}. \tag{25}$$

According to (23) the response of welfare to a small change in the ceiling policy (induced by de_{A1}) is determined by the income effect (24) and the price effect (25). Since the tax rates π_1 and π_2 are not sign-constrained, the signs of these effects are unclear. We consider (21), (24) and (25) in (23) to get, after some rearrangement of terms,

$$\frac{du_A}{de_{A1}} = \frac{u_A}{\gamma y_A}\left[(\pi_1 + \gamma \vartriangle e_A) - (\pi_1 - \overline{\gamma}\pi_2)\cdot G\right], \text{ where } G := \frac{\gamma\, p_x (x_{A2} + x_{B2}^s)}{x_1^s - \overline{\gamma}\, p_e \pi_2} > 0. \tag{26}$$

Equation (26) gives rise to the following results (proved in Appendix A.II).

Proposition 3.

(i) *Suppose* $\overline{e}_1 = e_1^0$. *Country A's cost-effective ceiling policy belongs to the set*

$$\begin{Bmatrix} E_\ell \\ \{\overline{e}_1/2\} \\ E_h \end{Bmatrix} \text{ with tax rates } \begin{Bmatrix} (\pi_1 > 0, \pi_2 > 0) \\ (\pi_1 = \pi_2 = 0) \\ (\pi_1 < 0, \pi_2 < 0) \end{Bmatrix} \text{ if and only if } \alpha_A \begin{Bmatrix} < \\ = \\ > \end{Bmatrix} 1/2.$$

(ii) Suppose $\overline{e}_1 < e_1^0$.

(a) If $\alpha_A \le 1/2$, *country A's cost-effective ceiling policy belongs to the set* $E_\ell \cup \{e_{A1}(\pi_2 = 0)\} \cup E_m$ *and exhibits* $\pi_1 > 0$. *The sign of* π_2 *is unclear.*

(b) If $\alpha_A \ge 1/2$ *and* $\gamma \ge 1/2$, *country A's cost-effective ceiling policy belongs to the set* $E_m \cup \{\overline{e}_1/2\} \cup E_h$ *and exhibits* $\pi_2 < 0$. *The sign of* π_1 *is unclear.*

Proposition 3(i) takes up the limiting case $\overline{e}_1 = e_1^0$ again and it demonstrates the link of the issue at hand with the standard theory of strategic international trade [Quellen?]. That link exists because carbon emissions are proportional to the consumption/burning of fossil fuel and because fossil fuel is traded on a world market. As a consequence, if country A imports fuel and taxes (at a positive rate) its domestic fuel consumption, that tax is also levied on the amount of fuel imported, and to that extent the tax is uno actu an import tariff on fossil fuel. The essential impact is that the tax diminishes the world demand for fossil fuel, ceteris paribus, and thus reduces the fossil fuel price because the global supply of fossil fuel is fixed. Country A's generates this terms-of-trade effect intentionally to reduce its fossil-fuel import bill. Conversely, if country A exports fossil fuel and taxes (at a negative rate) its domestic fuel consumption that (negative) tax is uno actu an export subsidy on fossil fuel. It raises the world demand for fossil fuel, ceteris paribus, and thus raises the fossil fuel price given the fixed global supply of fossil fuel. That terms-of-trade effect increases country A's revenues from exporting fossil fuel. In sum, the government of country A chooses its policy in an effort to manipulate the terms-of-trade effect in favor of its consumer. For $\bar{e}_1 = e_1^0$, the laissez-faire equilibrium with $e_{A1} = e_{A1}^0$ and $\pi_1 = \pi_2 = 0$ clearly qualifies as a ceiling policy. But equation (26) then reads

$$\left.\frac{du_A}{de_{A1}}\right|_{\substack{\bar{e}_1 = e_1^0 \\ \pi_1 = \pi_2 = 0}} = \frac{bu_A}{y_A} \vartriangle e_A$$

and it readily reveals the incentives of country A's government to deviate from the laissez-faire equilibrium. The government knows that it can do better when it acts strategically and chooses a ceiling policy with emission subsidies in both periods which is associated with a higher [lower] level of e_{A1}, if $\vartriangle e_A > 0$ [$\vartriangle e_A > 0$]. If $\vartriangle e_A > 0$, increasing e_{A1} raises p_e and with it the fuel export revenues, ceteris paribus. However, this favorable price effect is eventually neutralized by a countervailing quantity effect. That quantity effect arises because we have established in Proposition 2 above that e_{A2} increases along with e_{A1} such that increasing e_{A1} diminishes the amount of fuel exported ($\vartriangle e_A$). The government of country A seeks to balance both effects in an optimal way. Analogous arguments apply to the case $\alpha_A < 1/2$.

Proposition 3(ii) addresses the relevant case $\bar{e}_1 < e_1^0$ and confirms that under certain conditions cost-effectiveness requires an emission tax proper in the first period ($\pi_1 > 0$) and a second-period emission subsidy ($\pi_2 < 0$) under other conditions. It is worth emphasizing that there is no choice between alternative *cost-effective* ceiling policies as in the case of cooperative action (Section 3). Which of the feasible policies is the best one only depends on the countries' fossil fuel endowments.

Although the information gained in Proposition 3(ii) about country A's cost-effective policy is limited, the principal message appears to be similar to that of the case of the weakly binding ceiling $\bar{e}_1 = e_1^0$ in Proposition 2(i): When country A's fossil fuel stock is small [large] relative to that of country B, the cost-effective policy tends to be related to a relatively high [low] level of e_{A1}. We will further substantiate that insight by invoking (26) and rewriting the first-order condition for maximizing utility u_A in the following way.

$$\frac{du_A}{de_{A1}} = 0 \quad \Leftrightarrow \quad F(e_{A1}; \alpha_A) = H(e_{A1}), \text{ where} \tag{27}$$

$$F(e_{A1}; \alpha_A) := \pi_1(e_{A1}) + \gamma\left[\alpha_A \bar{e} - e_{A1} - e_{A2}(e_{A1})\right] \;\&\; H(e_{A1}) := \left[\pi_1(e_{A1}) - \bar{\gamma}\pi_2(e_{A1})\right] \cdot G(e_{A1}).$$

The term $G(e_{A1})$ defined in (26) depends on e_{A1} in a complicated way. For our purposes it suffices, however, to take advantage of the observation that under mild conditions[17] $G(e_{A1}) \in [0,1]$. In that case the graph of the function *H* is plotted in Figure 2 as the winding curve in the area between the curve $\pi_1 - \bar{\gamma}\pi_2$ and the e_{A1} axis. The function *F* is strictly

[17] For details on this constraint see the proof of Proposition 3(ii) in Appendix A.II.

decreasing in[18] e_{A1} and has the property that its graph shifts upward with increasing α_A. Figure 2 depicts four alternative graphs of *F* for different shares α_A. The greater the share α_A is, the further to the right is the graph of *F*. The cost-effective ceiling policy is determined by the intersection point of the graphs of *F* and *H*. The straightforward implication is that the greater is country A's share α_A of the world stock of fossil fuel, the higher is the level of e_{A1} that characterizes the cost-effective ceiling policy. If for low shares α_A the cost-effective policy is in E_ℓ, it moves into E_m and likely further into E_h with successively increasing α_A. The information added by Figure 2 to the results of Proposition 3 is that the level of e_{A1} in the cost-effective policy rises smoothly with share α_A. Unfortunately. however, Figure 2 does not provide rigorous conditions under which the cost-effective policy belongs to a specific subset of *E*.

5 Concluding remarks

This paper builds on the proposition that reducing climate change damage requires curbing worldwide carbon emissions in the near to medium future (ceiling policy) and is therefore conceptually in line with the political goal of keeping the world mean temperature from exceeding 2° Celsius above preindustrial levels. In view of more than two decades of international climate negotiations the prospects for a fully cooperative ceiling policy appear to be bleak. On the other hand, several countries are taking action to abate domestic emissions and/or have announced to do so in the near future. But owing to free riding and carbon leakage, the net effects of such uncoordinated unilateral policies on global medium term emissions are unclear in the aggregate as well as for individual countries. That could be different, if the 'willing countries' would cooperate in a subglobal climate coalition, as we assume in the present paper. Although carbon leakage is still an issue in that case, such a coalition can implement some agreed upon medium-term global emission ceiling in joint action and can, conceptually at least, calculate the cost accruing to the coalition. Moreover, the coalition can choose among a set of policies that meet the same ceiling but differ in costs. It is therefore natural to go for that particular ceiling policy which meets the given carbon ceiling at minimum cost for the coalition.

We have characterized the unilateral feasible ceiling policies and the cost-effective policy and have compared that regulation with the fully cooperative cost-effective ceiling policy. We found that the unilateral cost-effective policy requires regulating the coalition's emissions in all periods while in case of full cooperation cost-effectiveness can be attained through a ceiling policy consisting of a world-wide emissions tax levied in the first period only that is uniform across countries. Interestingly, under some conditions the unilateral cost-effective policy calls for emission subsidies rather than emission taxes. The sign and size of these taxes turns out to depend on the share of the world stock of fossil energy owned by the climate coalition.

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[18] Single-peakedness of the function u_A from (22) requires that $F_{e_{A1}} < H_{e_{A1}}$ for all e_{A1}. Although sign and size of $H_{e_{A1}}$ are unclear, the derivative $F_{e_{A1}} = -2-\gamma\left(1+\frac{de_{A2}}{de_{A1}}\right) < -(2+\gamma)$ is very small which is why $F_{e_{A1}} < H_{e_{A1}}$ for all e_{A1} is very likely.

The price to be paid for the substantive analytical results achieved in the paper is simplifying assumptions. Our model consists of two periods and two countries only and applies, in addition, parametric functions for production and utility. The countries are alike except for their stock of fossil energy resources, and the negative climate externality being the raison d'être for climate policy is not contained in the formal model. Eichner and Pethig (2010) show that omitting consumption externalities, abatement technologies and multiple periods is not an essential restriction - although it would prevent us from reaching analytical results. Since it is the expected cost of climate policy that deters countries from taking action the quest for cost-effectiveness is indispensible for making progress. Therefore, more work is necessary on the characterization of cost-effective subglobal ceiling policy. But the restrictions one is forced to accept for obtaining *analytical* results suggest that this work should be carried out in large-scale, less stylized models which are calibrated with realistic empirical data.

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Appendix

Appendix A.I *Proof of Proposition 2*

Since the proofs of different parts of Proposition 2 are interrelated, the subsequent proof does not follow the sequence of results as listed in Proposition 2.

Ad Prop. 2(iii), first sentence. To determine how ceiling policies differ in their respective equilibriums, we will leave the ceiling $\bar{e}_1$ unchanged but will disturb the initial equilibrium by a small (exogenous) variation in e_{A1} and determine the displacement effects characterizing the new competitive equilibrium reached after the shock. Total differentiation of the equations (4) for t = 1, (6), (19), (20) and (21) leads to

$$d\pi_i = -2de_{Ai}, \qquad i = A, B, \tag{A1}$$

$$dp_e = bde_{A1}, \qquad i = A, B, \tag{A2}$$

$$\frac{p_e}{p_x}dp_x + bp_x de_{A2} = dp_e, \tag{A3}$$

$$dx_{i1} = \gamma dy_i, \qquad i = A, B, \tag{A4}$$

$$dx_{i2} = \frac{x_{i2}}{y_i}dy_i - \frac{x_{i2}}{p_x}dp_x, \qquad i = A, B, \tag{A5}$$

$$dy_A = b\pi_1 de_{A1} + bp_x\pi_2 de_{A2} + \vartriangle e_A dp_e + x^s_{A2} dp_x\,, \tag{A6}$$

$$dy_B = -\vartriangle e_A dp_e + x^s_{B2} dp_x\,, \tag{A7}$$

$$\pi_1 de_{A1} = dx_{A1} + dx_{B1}\,. \tag{A8}$$

$\dfrac{d\pi_1}{de_{A1}} = -2 < 0$ and $\dfrac{dp_e}{de_{A1}} = b > 0$ are obvious from (A1) and (A2). Next put dp_e from (A2) into (A3) and consider the equations (A4), (A5) and (A7) in (A8) to obtain

$$\frac{p_e}{p_x} dp_x + bp_x de_{A2} = bde_{A1} \quad \text{and} \quad \bar{\gamma} x^s_2 dp_x + b\bar{\gamma}\, p_x \pi_2 de_{A2} = b\pi_1 de_{A1}\,.$$

Solving these two equations for dp_x and de_{A2} yields

$$\frac{dp_x}{de_{A1}} = \frac{bp_x\left(\pi_1 - \bar{\gamma}\pi_2\right)}{\bar{\gamma}\left(p_x x^s_2 - p_e\pi_2\right)} = \frac{bp_x\left(\pi_1 - \bar{\gamma}\pi_2\right)}{x^s_1 - \bar{\gamma}\, p_e \pi_2} \tag{A9}$$

and $\dfrac{de_{A2}}{de_{A1}} = \dfrac{x^s_1 - p_e\pi_1}{p_x\left(x^s_1 - \bar{\gamma}\, p_e\pi_2\right)} = \dfrac{x^s_1 - p_e\pi_1}{\bar{\gamma}\, p_x\left(p_x x^s_2 - p_e\pi_2\right)}$. Note that $p_x x^s_2 - p_e\pi_2 = p_x x^s_{A2} + p_e e_{A2} + p_x x^s_{B2} - p_e e_{B2} > 0$, because the profit $p_x x^s_{B2} - p_e e_{B2}$ is positive. Likewise, $x^s_1 - p_e\pi_1 > 0$ and therefore $de_{A2}/de_{A1} > 0$. From (A1) and $de_{A2}/de_{A1} > 0$ follows $\dfrac{d\pi_2}{de_{A1}} = -2\dfrac{de_{A2}}{de_{A1}} < 0$.

Ad Prop. 2(iv)(b). π_1 and π_2 have been shown to be strictly decreasing in e_{A1} over E in the proof of the first sentence of Prop. 2(i) above. We proceed in several steps.

Claim I: $\bar{e}_1 \begin{Bmatrix} < \\ = \end{Bmatrix} e^0_1$ *implies* $\dfrac{x^{s*}_1}{x^{s*}_2} \begin{Bmatrix} < \\ = \end{Bmatrix} \dfrac{x^{s0}_1}{x^{s0}_2} = \bar{\gamma}\, p^0_x$ *with* $x^{s*}_t := a\bar{e}_t - \dfrac{b\bar{e}^2_t}{4}$ *and* $x^s_t := x^s_{At} + x^s_{Bt}$.

Observe first that the equations (4), (6) and (21) imply

$$x^s_1 = \bar{\gamma}\, p_x x^s_2 \tag{A10}$$

which holds in laissez-faire as well as with ceiling regulation. In the latter case we have

$$x^s_t = a\bar{e}_t - \frac{b}{2}\bar{e}^2_t + be_{At}e_{Bt} = a\bar{e}_t - \frac{b}{2}\bar{e}^2_t - \frac{b}{4}\bar{e}^2_t + \frac{b}{4}\bar{e}^2_t + be_{At}e_{Bt} = x^{s*}_t - b\left(\frac{\bar{e}^2_t}{4} - e_{At}e_{Bt}\right). \tag{A11}$$

x^{s*}_t is the maximum possible production in t under the constraint $\bar{e}_t$ which is attained if and only if $e_{At} = e_{Bt}$ or, equivalently, if and only if $\pi_t = 0$. Claim I is verified because $x^{s*}_1 < x^{s0}_1$ and $x^{s*}_2 > x^{s0}_2$, if $\bar{e}_1 \le e^0_1$, and $x^{s*}_1 = x^{s0}_1$ and $x^{s*}_2 = x^{s0}_2$ if $\bar{e}_1 = e^0_1$.

$\bar{e}_1 < e^0_1$ has been presupposed.

Claim II: *If* $\left(\pi_1, \pi_2 = 0\right)$ *is a ceiling policy for* $\bar{e}_1 \begin{Bmatrix} < \\ = \end{Bmatrix} e^0_1$, *then* $\bar{\gamma}\, p^0_x \begin{Bmatrix} > \\ = \end{Bmatrix} \dfrac{x^s_1}{x^s_2} = \bar{\gamma}\, p_x$

In the economy with ceiling regulation the commodity market equilibriums require (as shown above) $\frac{x_1^s}{x_2^s} = \frac{x_1^{s*} - b\left(\frac{\overline{e}_1^2}{4} - e_{A1}e_{B1}\right)}{x_2^{s*} - b\left(\frac{\overline{e}_2^2}{4} - e_{A2}e_{B2}\right)}$. As $\pi_2 = 0$ implies $e_{A2} = e_{B2} = \overline{e}_2 / 2$, it follows that $x_2^s = x_2^{s*}$. Moreover, $(\pi_1 = 0, \pi_2 = 0)$ is a ceiling policy, if and only if $\overline{e}_1 = e_1^0$. Otherwise we must have $\pi_1 \neq 0$ and hence $x_1^s < x_1^{s*}$. Combined with Claim I these findings prove Claim II.

Claim III: If $(\pi_1, \pi_2 = 0)$ is a ceiling policy for $\overline{e}_1 < e_1^0$, then $\pi_1 > 0$.

Contrary to the claim suppose that $(\pi_1 \leq 0, \pi_2 = 0)$ is a ceiling policy. In that case we have $p_e = a - be_{B1} = p_x\left(a - b\overline{e}_2 / 2\right)$, $e_{B1} \leq \overline{e}_1 / 2$ and therefore $p_x \geq \frac{2a - b\overline{e}_1}{2a - b\overline{e}_2}$. In the laissez-faire economy we calculate $p_x^0 = \frac{2a - be_1^0}{2a - be_2^0}$ which is smaller than $\frac{2a - b\overline{e}_1}{2a - b\overline{e}_2}$ because of $\overline{e}_1 < e_1^0$. We conclude that $p_x^0 = \frac{2a - be_1^0}{2a - be_2^0} < \frac{2a - b\overline{e}_1}{2a - b\overline{e}_2} \leq p_x$. However, $p_x < p_x^0$ follows from Claim II. That contradiction proves Claim III and thus Proposition 2(iv)(b).

Ad Prop. 2(i). Suppose first that $\overline{e}_1 < e_1^0$ and observe that $e_{A1}(\pi_2 = 0) < \overline{e}_1 / 2$ holds because $\pi_1 > 0$ at $e_{A1}(\pi_2 = 0)$ according to Proposition 2(iv)(b) and because π_1 is strictly decreasing in e_{A1} according to (A1). Hence the level of e_{A1} at which π_1 becomes zero, is greater that $e_{A1}(\pi_2 = 0)$. In fact, we have $e_{A1}(\pi_1 = 0) = \overline{e}_1 / 2 > e_{A1}(\pi_2 = 0)$ which proves $E_m \neq \emptyset$. From $\overline{e}_1 = e_1^0$ follows $e_{A1}(\pi_1 = 0) = e_{A1}(\pi_2 = 0) = \overline{e}_1 / 2$ and therefore $E_m = \emptyset$.

Ad Prop. 2(iv) (cont'd). We have shown in the proof ofr the first sentence of Prop. 2(iii) above that π_1 and π_2 are strictly decreasing over the entire interval *E*. Combined with the result of Prop. 2(iv)(b), that observation completes the proof of Proposition 2(iv).

Ad Prop. 2(iii), second sentence. Recall from Proposition 2(iv)(c) that $\pi_1 > 0$ and $\pi_2 < 0$ over the interval E_m which implies $\pi_1 > \overline{\gamma}\pi_2$ and $dp_x / de_{A1} > 0$ via (A9). It remains to show that p_x is strictly monotone increasing over E_ℓ (as over E_m) but not over E_h. To that end we calculate the ceiling policies that are feasible for predetermined $p_x = \overline{p}_x$ (and endogenized e_{A1}). For some fixed $\overline{p}_x$ equation (10) yields $\overline{p}_x\left(a - b\overline{e}_2 + be_{A2}\right) = = a - b\overline{e}_1 + be_{A1}$ and after rearrangement of terms,

$$e_{A1} = k + \overline{p}_x e_{A2}, \qquad \text{where } k := \frac{\left(a - b\overline{e}_2\right)\overline{p}_x - \left(a - b\overline{e}_1\right)}{b}. \tag{A12}$$

The second equation we need for determining e_{A1} and e_{A2} is generated from combining (A10) and (A11): We find that $a\overline{e}_1 - \frac{b}{2}\overline{e}_1^2 + b\left(\overline{e}_1 e_{A1} - e_{A1}^2\right) = \overline{\gamma}\, p_x x_2^s$ and rewrite that equation as

$$e_{A1}^2 - \overline{e}_1 e_{A1} + \frac{1}{b}\left(\overline{\gamma}\, p_x x_2^s - \frac{2a\overline{e}_1 - b\overline{e}_1^2}{2}\right) = 0\,. \tag{A13}$$

Note that $x_1^s = \overline{\gamma}\, p_x x_2^s$ and $\frac{2a\overline{e}_1 - b\overline{e}_1^2}{2} \leq x_1^s$ according to (A10) and (A11), respectively. The inequality sign holds, if and only if $e_{A1} = 0$. Hence in (A13) the bracketed term is positive for all $e_{A1} \in \left]0, \overline{e}_1\right]$ which implies that if (A13) has two solutions, both values of e_{A1} are in the relevant domain $\left[0, \overline{e}_1\right]$ and therefore need to be accounted for. The solution of (A13) is $e_{A1} = \frac{\overline{e}_1}{2} \pm \sqrt{\frac{1}{b}\left(x_1^{s*} - \overline{\gamma}\,\overline{p}_x x_2^s\right)}$ yielding

$$e_{A1}^{(+)} = G^{(+)}\left(e_{A2}\right) := \frac{\overline{e}_1}{2} + \sqrt{\tfrac{1}{b}\left[x_1^{s*} - \overline{\gamma}\,\overline{p}_x\left(a\overline{e}_2 - \tfrac{b}{2}\overline{e}_2^2\right) - \overline{\gamma}\,\overline{p}_x\left(\overline{e}_2 e_{A2} - e_{A2}^2\right)\right]}\,, \tag{A14}$$

$$e_{A1}^{(-)} = G^{(-)}\left(e_{A2}\right) := \frac{\overline{e}_1}{2} - \sqrt{\tfrac{1}{b}\left[x_1^{s*} - \overline{\gamma}\,\overline{p}_x\left(a\overline{e}_2 - \tfrac{b}{2}\overline{e}_2^2\right) - \overline{\gamma}\,\overline{p}_x\left(\overline{e}_2 e_{A2} - e_{A2}^2\right)\right]}\,. \tag{A15}$$

The function $G^{(+)}$ is u-shaped and the function $G^{(-)}$ is inversely u-shaped. The only point in common is $\left(e_{A1} = \overline{e}_1/2, e_{A2} = \overline{e}_2/2\right)$ but that point is no candidate for a ceiling policy. As a consequence, the points of intersection between (A12) on the one side and (A14) and (A15) on the other side have the following property: either their e_{A2} coordinates are all smaller than $\overline{e}_2/2$ or their e_{A2} coordinates are all larger than $\overline{e}_2/2$. Suppose all points of intersection exhibit $e_{A2} < \overline{e}_2/2$. Then we infer from (A12) and (A14) that there is an intersection point $\left(\tilde{e}_{A1}, \tilde{e}_{A2}\right)$ satisfying $\tilde{e}_{A2} < \overline{e}_2/2$, $\tilde{e}_{A1} > \overline{e}_1/2$, and $\tilde{e}_{A1} := G^{(+)}\left(\tilde{e}_{A2}\right) = = k + \overline{p}_x \tilde{e}_{A2}$ However, that point is incompatible with a ceiling policy because we have shown above that if there is a ceiling policy with $e_{A1} > \overline{e}_1/2$, then e_{A2} is required to satisfy $e_{A2} > \overline{e}_2/2$. It follows that the solutions of (A12), (A14) and (A15) define feasible ceiling policies if and only if their e_{A2} coordinate is larger than $\overline{e}_2/2$. It remains to clarify whether there are multiple solutions. If so, p_x would not be monotone increasing over the entire domain E. To begin with, there exists a solution of (A12) and (A15) satisfying $\left(\hat{e}_{A1} < \overline{e}_1/2, \hat{e}_{A2} > \overline{e}_2/2\right)$ because in the sub-domain $\left[\overline{e}_2/2, \overline{e}_2\right]$ the function $G^{(-)}$ is downward sloping and (A12) is upward sloping. Clearly, $\left(\hat{e}_{A1} < \overline{e}_1/2, \hat{e}_{A2} > \overline{e}_2/2\right)$ represents a ceiling policy in E_m. Since both (A12) and $G^{(+)}$ are upward sloping on $\left[\overline{e}_2/2, \overline{e}_2\right]$ there is either no point of intersection, or only such point or multiple points. As one can always 'generate' more than one intersection point through via a suitable choice of the size of $\overline{p}_x$, we conclude that p_x is not monotone increasing over the domain E_h.

Ad Prop. 2(ii). Consider first the policy $\left(\pi_1 > 0, \pi_2 = 0\right)$ and observe that $e_{B1} > \overline{e}_1/2 > e_{A1}$ owing to $\pi_1 > 0$. In view of (20) that leads to $p_e = a - be_{B1} < a - b\left(\overline{e}_1/2\right)$ $<$ $< a - b\left(e_1^0/2\right) = p_e^0$. $p_x < p_x^0$ follows from Claim II. We have established that p_x and p_e are increasing in e_{A1} over E_ℓ. That completes the proof of Prop. 2(ii).

Appendix A.II *Proof of Proposition 3.*

Ad Prop. 3(i). For $\pi_1 = \pi_2 = 0$ and $\overline{e}_1 = e_1^0$ we are in the laissez-faire equilibrium. The only way the countries A and B may differ from each other are differing fossil fuel ownership shares α_A and α_B. If $\alpha_A = \alpha_B$ no trade in fossil fuel and the commodity takes place ($\vartriangle e_A = 0$). Since the fuel demands are $e_{At} = e_{Bt} = \overline{e}_t / 2$ for t = 1, 2, it is straightforward that in the laissez-faire equilibrium we have $\vartriangle e_A \gtrless 0$ if and only if $\alpha_A \gtrless \alpha_B$. Combining this information with the single-peakedness of (22) and with $\left.\frac{du_A}{de_{A1}}\right|_{\substack{\pi_1=\pi_2=0\\ \overline{e}_1=e_1^0}} = \frac{bu_A}{y_A} \vartriangle e_A$ from (26) completes the proof.

Ad Prop. 3(ii)(a). Consider the feasible ceiling policy $\left(\pi_1 = 0, \pi_2 < 0\right)$ as point of departure. In the corresponding equilibrium, country A's fossil fuel consumptions are $e_{A1} = \overline{e}_1 / 2$ and $e_{A2} > \overline{e}_2 / 2$ and hence $e_{A1} + e_{A2} > \overline{e} / 2$. From the presupposition $\alpha_A \le 1/2$ follows $\vartriangle e_A < 0$ such that (26) implies

$$\frac{du_A}{de_{A1}} = \frac{u_A}{\gamma y_A}\left(\gamma \vartriangle e_A + \overline{\gamma} \pi_2 G\right) < 0 .$$

Single-peakedness of u_A in e_{A1} then establishes Prop. 3(ii)(a).

Ad Prop. 3(ii)(b). Now we take the feasible ceiling policy $\left(\pi_1 > 0, \pi_2 = 0\right)$ as point of departure. In the corresponding equilibrium, country A's fossil fuel consumptions are $e_{A1} < \overline{e}_1 / 2$ and $e_{A2} = \overline{e}_2 / 2$ and hence $e_{A1} + e_{A2} < \overline{e} / 2$. From the presupposition $\alpha_A \ge 1/2$ follows $\vartriangle e_A > 0$ such that (26) implies

$$\frac{du_A}{de_{A1}} = \frac{u_A}{\gamma y_A}\left[\pi_1\left(1-G\right) + \gamma \vartriangle e_A\right] > 0.$$

Single-peakedness of u_A in e_{A1} establishes Prop. 3(ii)(b) if $G \in \left[0,1\right]$. By definition,

$$G := \frac{\gamma p_x\left(x_{A2} + x_{B2}^s\right)}{x_1^s - \overline{\gamma}\, p_e \pi_2} \text{ and } G = \frac{\left(1-\gamma\right) p_x\left(x_{A2} + x_{B2}^s\right)}{p_x x_2^s} \text{ since } \pi_2 = 0\text{. Therefore}$$

$$G < 1 \quad \Leftrightarrow \quad \left(1-\gamma\right) p_x\left(x_{A2} + x_{B2}^s\right) < p_x x_2^s$$

$$\Leftrightarrow \quad 0 < p_x\left[x_{A2}^s + x_{B2}^s - \left(1-\gamma\right) x_{B2}^s - \left(1-\gamma\right) x_{A2}\right] = p_x\left[x_{A2}^s + \gamma x_{B2}^s - \left(1-\gamma\right) x_{A2}\right]$$

$$= p_x\left[\gamma\left(x_{A2}^s + x_{B2}^s\right) + \left(1-\gamma\right) x_{A2}^s - \left(1-\gamma\right) x_{A2}\right] = p_x\left[\gamma x_2^s - \gamma x_2 + \gamma x_2 + \left(1-\gamma\right) x_{A2}^s - \left(1-\gamma\right) x_{A2}\right]$$

$$= p_x\left[\gamma x_{A2} + \gamma x_{B2} + \left(1-\gamma\right) x_{A2} + \left(1-\gamma\right) x_{A2}^s\right].$$

$$G < 1 \quad \Leftrightarrow \quad 0 < \left(2\gamma - 1\right) p_x x_{A2} + p_x\left[\gamma x_{B2} + \left(1-\gamma\right) x_{A2}^s\right] \quad \Leftrightarrow \quad \gamma > \frac{1}{2} - \frac{\gamma x_{B2} + \left(1-\gamma\right) x_{A2}^s}{2 x_{A2}}.$$

The right side of the last inequality is less than ½ and may even be negative. Hence the qualification $\gamma \geq 1/2$ in Prop. 3(ii)(b) is a very weak sufficient condition.