WORKING PAPER SERIES

Cap-and-Trade Policy vs. Carbon Taxation: Of Leakage and Linkage

Hendrik Ritter/Karl Zimmermann

Working Paper No. 03/2019

OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG

FACULTY OF ECONOMICS AND MANAGEMENT

Impressum (§ 5 TMG)

Herausgeber:

Otto-von-Guericke-Universität Magdeburg
Fakultät für Wirtschaftswissenschaft
Der Dekan

Verantwortlich für diese Ausgabe:

Hendrik Ritter and Karl Zimmermann
Otto-von-Guericke-Universität Magdeburg
Fakultät für Wirtschaftswissenschaft
Postfach 4120
39016 Magdeburg
Germany

http://www.fww.ovgu.de/femm

Bezug über den Herausgeber

ISSN 1615-4274

Cap-and-Trade Policy vs. Carbon Taxation: Of Leakage and Linkage

Hendrik Ritter* • Karl Zimmermann†

April 3, 2019

Abstract

We assess a 2-period, non-cooperative equilibrium of an n country policy game where countries chose either (i) carbon taxes, (ii) cap-and-trade policy with local permit markets or (iii) cap-and-trade policy with internationally linked permit markets and potential central redistribution of permit revenues. Policy makers maximizes welfare, which depends on household consumption over time and environmental damage from period-1 resource use. We assume costless and complete extraction of this non-renewable resource, so damage only depends on speed of extraction. Tax policy is the least efficient option due to carbon leakage, which introduces a second externality adding to the environmental externality. Cap-and-trade policy does not show any leakage since all symmetric countries will employ caps. Its equilibrium thus only suffers from the environmental externality and welfare is higher than under carbon taxation. The policy scenario with linked permit markets and central redistribution yields an efficient outcome. The redistribution of revenues creates a negative externality which offsets the positive environmental externality.

Keywords: Climate Policy • Carbon Tax • Cap-and-Trade Policy • Linked Permit Markets

JEL Classification: H23 • Q38 • Q54 • Q58

*Faculty of Economics and Management, Otto–von–Guericke University Magdeburg, Postbox 4120, 39016 Magdeburg, Germany, e-mail: hendrik@ritter.me, phone: +49 391 6758545.

†Faculty of Economics and Business, Universidad Anahuac Mexico, Av. de las Torres 131, Col. Olivar de los Padres, Del. Álvaro Obregón, Mexico City, Mexico, e-mail: karl.zimmermann@anahuac.mx

1 Introduction

Oil, natural gas, coal – in short fossil fuels – have been a main pillar of economic growth and prosperity – at least since the industrial revolution. Although scientific research has found much evidence for harmful anthropogenic climate change, caused by the intensive use of fossil fuels,[1] there are indications that fossil fuels will remain a major source of energy in the world economy. According to the International Energy Agency, the era of oil is not yet over. They forecast that global oil demand will increase until 2040.[2] Others claim that at least conventional fossil fuel sources might be fully exploited over the next decades due to the slow transition towards renewable sources of energy (Shafiee and Topal, 2009; Fouquet, 2010; Höök and Tang, 2013).

The adverse effects of greenhouse gas emissions on the other hand require policy action. The literature finds that the socially optimal extraction path of non-renewable resources is slower than the *laissez-faire* extraction path, if extraction (or resource use) produces negative externalities. This holds if damages depend on the stock of accumulated emissions, see Withagen (1994) and Golosov et al. (2014) and others, or if damages depend mainly on the change of the emission stock, i. e. the pace of greenhouse gas accumulation and therefore climate change (Tahvonen, 1995; Hoel and Kverndokk, 1996). To incentivize a postponement of supply, in general, it is optimal to implement a carbon pricing policy, where present value carbon fees are non-increasing over time. However, if no first-best policy is implemented, which is most likely the case in the real world, extraction will be too fast, resulting in inefficiently high damage from climate change.

In applied politics, there is in deed evidence for rising "climate action" in various countries in the past decades (Iacobuta et al., 2018). Yet apart from the question whether such initiatives where sufficiently ambitious, a clear shortcoming of climate policy was and still is that it has been implemented at regional levels at best, such as the EU Emission Trading System (EU ETS), but mostly at national or even subnational levels due to a lack in international cooperation.[3] Climate change mitigation in one country or region causes positive interregional externalities elsewhere by reducing climate damages. Not taking into account these benefits of reduced damage outside its own territory, a policy maker will implement an inefficiently low level of mitigation. The presence of such spillovers leads to possibly insufficient participation and ineffective international environmental agreements and therefore inefficiently high environmental damage, see Barrett (1994) and others.

Another spillover comes into play when considering international mobility on factor and goods markets. Carbon leakage, the offset of emission abatement in one country

[1] See IPCC (2013)

[2] IEA 2018: World Energy Outlook 2017, `https://www.iea.org/weo2017/#section-3-1`

[3] The United Nations Framework Convention on Climate Change (UNFCCC) gives testimony where a shift in global climate governance from aiming at "globally agreed" emission reduction targets (UNFCCC Conference of the Parties Copenhagen 2009) to "nationally determined" reduction targets (2015 Paris Accord) could be observed (Cramton et al., 2017; Iacobuta et al., 2018).

through the rise in emissions elsewhere, reduces the effectiveness of mitigation policies. In their review, Chen and Woodland (2013) conclude that the theoretical literature is quite inconclusive as to whether leakage is positive, negative or even insignificant, while assessments based on computable general equilibrium models in general indicate positive leakage rates. The leakage intensity depends on the structural factors of the implementing economy as well as the type of policy that is implemented. In that respect, Krishna (2011) points out that in the case of large open economies, which have an impact on global factor prices, a higher carbon tax or tighter cap will lead to carbon leakage unless there are quantitative carbon controls in the rest of the world, i. e. cap-and-trade policy. So, in a world with complete international application of (binding) caps, there will be no leakage, as opposed to a world where all countries employ carbon taxes (or other non-quantity-based instruments like green energy subsidies). On the other hand, price based carbon policies (like taxes) do not exhibit a lower bound issue, i. e. there could be a carbon subsidy, while permit prices in emission trading systems cannot fall below zero. Hoel and Kverndokk (1996) show that in special cases the optimal carbon tax trajectory could consist of negative taxes in some point of time yet not throughout. In practice, both types of instruments have been implemented in a number of countries. Since the 1990s carbon taxes have been introduced in 17 countries and emission trading schemes (ETS's) in 55 countries (Haites, 2018).[4]

These observations lead to our research question: Is extraction slowed down more effectively in a world with carbon taxes or in a world with cap-and-trade policies considering international trade on factor and goods markets and non-cooperative policy makers. In order to address our research question, we employ a 2-period model of n identical jurisdictions. A homogeneous non-renewable natural resource (henceforth *resource*) is exploited costlessly over time and traded globally. Each jurisdiction's local firm produces the homogeneous consumption good, while the resource serves as the only production factor. These firms are subject to local climate policy, i. e. a carbon tax or an emission cap, which is set by local governments. Private households obtain utility from consumption in both periods and undertake consumption smoothing. Local governments in turn maximize local welfare, here the balance of lifetime consumption utility and local environmental damage, by applying one of the discussed policy instruments. The policy makers take each other's strategies as given (Nash conjecture), but take the private actors' reactions to policy parameters into account. In our model, environmental damage depends on the steepness of the extraction path, as the resource is always fully depleted. We consider general equilibrium aspects by endogenously determining market prices including the discount rate and recycling profits from local firms and resource rents as household income. Furthermore, the resource extractor considers the households' intertemporal rate of substitution as its discount rate to maximize its shareholder value. We study both policy

[4]In all cases these schemes do cover only some economic sectors. Moreover, many countries employ both types of policies side by side to achieve greater coverage of greenhouse gas emissions.

instruments in separate scenarios, meaning that we assume that all countries employ either carbon taxes or cap-and-trade schemes.

We obtain the following results. Firstly, with respect to carbon taxation we find that unilaterally raising the tax rate in the first (second) period slows down (accelerates) extraction. The reason is as follows. Within the same period, the tax distorts the factor market, putting downward pressure on the factor price. Due to the Hotelling rule, the resource extractor is encouraged to flatten (incline) the extraction path. On the other hand, with postponement (front-loading) of extraction, total production of consumption goods is shifted to the future (present). Again, via the Hotelling rule, the resulting adjustment of the household discount rate attenuates the change in extraction speed. In line with the literature, the equilibrium carbon tax schedule is less steep than the fossil fuel price path, in our case we have a first-period tax and a second-period subsidy.[5] Leakage comes into play since resource demand partially relocates to other jurisdictions within the period in which the tax change occurs. This in turn lowers the effectiveness of the instrument to alter the extraction path and thus its impact on environmental damage.

Secondly, for the cap-and-trade policy we find that jurisdictions set binding caps only in period 1, while they abstain from doing so in period 2. The rationale behind this is that environmental damage in our model only depends on first-period extraction; so there is no use in limiting emissions in the second period. When countries choose identical policies, a cap reduction by one country in period 1 directly translates into postponement of extraction, as fossil fuel consumption in other countries is constrained by the local cap. Consequently, there is no leakage.

Thirdly, comparing the policy equilibria of both scenarios, we find that welfare is higher under the cap-and-trade policy than under carbon tax policy. We can show that environmental damage in the former case is closer to the *first-best* policy choice. This stems from the effectiveness of limiting emissions with the help of caps, which can be explained by the absence of carbon leakage when using this instrument.

There have been numerous contributions comparing quantity and price based policy instruments, following the seminal contribution of Weitzman (1974). An overview is found in Cropper and Oates (1992) and more recently in Goulder and Schein (2013). Under certain circumstances, determining either the quantity or the price of carbon might be advantageous, e. g. uncertain abatement cost or climate damages, carbon price volatility, openness of the economy and concerns about competitiveness as well as strategic reactions by the supply side of fossils and possible wealth transfers.

Regarding our research question, the literature focusing on strategic interaction in climate policy highlights that due to carbon leakage equilibria where all jurisdictions employ carbon taxes yield lower welfare than equilibria with ETS's. Hoel (2005) as well as Sim and Lin (2018) show this when countries have multiple industries of different pollution intensities, while Kiyono and Ishikawa (2013) and Eichner and Pethig (2015)

[5] See e. g. Sinclair (1994).

assume that there are clean goods as an (imperfect) substitute for dirty goods. All of these contributions assume trade in fossil fuel or final goods, provoking changes of relative prices or resource prices, which in turn cause the leakage effect when carbon taxes are employed. Tsakiris et al. (2017) show that the leakage effect prevails also if emissions are modeled as a by-product and the traded production factor is capital.

Our contribution is to analyze the aforementioned questions in a general equilibrium, n country, two-period model. Considering a dynamic perspective is essential as regards climate policy, from our point of view. And accounting for economy-wide impact of activities based on fossil fuel use, the same reasoning applies to general equilibrium effects. Most importantly, the fossil fuel supply (path) as well as the discount rate of the resource extracting firm are determined endogenously. Applying general functional forms makes our results more robust against specific assumption, but limits the analysis to the symmetric case.

As an extension, we assess a proposal of intermediate cooperation for a world with cap-and-trade policy, which consists in linking national permit markets. This is motivated firstly by the literature on the international linking of permit markets. For an overview, see Flachsland et al. (2009). Most of those analyses are dedicated to identify benefits and drawbacks in the context of heterogeneous countries or market structures, where the main argument is to increase cost-effectiveness by equalization of marginal abatement costs across countries. Carbone et al. (2009) find potentially significant reductions of global emissions by enacting a linking agreement. Secondly, in the real world, a number of linking initiatives could be observed recently. Just take the cases of California and Quebec in 2014, and the EU and Switzerland in 2016, where emission trading schemes have been joined, see Narassimhan et al. (2018).

We show how moderate coordination or centralization may help to achieve higher welfare. We find that if countries agree to link their permit markets and to create a revenue distribution scheme where all permits are auctioned off and revenues are distributed by evenly, they can achieve the first-best allocation. The technical rationale behind this result is that through the redistribution scheme countries can impose a negative policy externality on other countries. When tightening the local permit supply, the loss of revenues is distributed to all countries. This way each country's policy maker has the incentive to tighten its permit supply below the non-cooperative equilibrium level in the local permit markets scenario.

This paper is organized as follows: Section 2 presents the model extensively and derives the policy equilibrium for the carbon taxation scenario. Section 3 describes the model economy in a world with cap-and-trade policy and derives the policy equilibrium for local permit markets, while Section 4 does so for the case of linked permit markets. Section 5 presents the welfare analysis and establishes the main results of the paper. Finally Section 6 concludes.

2 A World with Carbon Taxation Policy

2.1 Market Equilibrium

Consider a model economy with $n \geq 2$ identical countries and two periods, the present ($t = 1$) and the future ($t = 2$) and suppose there is a representative **local firm** in each country. This firm produces a consumption good using a natural resource. The universal production technology is depicted by a concave production function $F(e_{it})$, where e_{it} represents resource input in country $i \in \{1, \ldots, n\}$ at time t and which satisfies $F' > 0$, $F'' < 0$, and $\lim_{e_{it} \to 0} F' = \infty$. These assumptions imply decreasing returns to scale of $F(e_{it})$ in e_{it}, which we motivate by assuming that production also relies on the invariant input of an immobile, local production factor such as land – suppressed for notational convenience.

In each period t, the firm purchases the resource on the world market at price p_t and sells its output at a price normalized to unity. Next to that, the firm also pays a local tax rate τ_{it} per unit of resource employed in production. The firm, which maximizes profits by the choice resource input, thus solves the problem given by

$$\max_{e_{it}} \qquad \pi_{it} = F(e_{it}) - [p_t + \tau_{it}]\, e_{it}. \tag{1}$$

Its optimal choice must satisfy

$$F'(e_{it}) = p_t + \tau_{it}, \tag{2}$$

which is the first-order condition of (1). Thus, the firm chooses e_{it} such that marginal productivity of the resource F' equals the gross factor cost $p_t + \tau_{it}$ per unit of input. Due to decreasing returns to scale, firm profits are positive in the optimum. This can be seen by inserting (2) into (1), which yields $\pi_{it} > 0$ since the concavity of $F(\cdot)$ implies $F(e_{it}) - e_{it}F'(e_{it}) > 0$.

The resource used in production is supplied by a representative global **extraction firm**. This firm exploits the world's non-renewable resource stock $\bar{e}$ over the course of the two periods. For the sake of tractability, we abstract from stock dependent extraction costs and assume that fixed costs of this firm are negligible. We assume, the firm maximizes net present value of periodical profits by determining the supply in each period (e_t^s), given the resource constraint set by $\bar{e}$, the resource prices p_1 and p_2, and the discount rate r. Its optimization problem is formally given by

$$\max_{e_1^s, e_2^s} \qquad \pi^R = \pi_1^R + \frac{\pi_2^R}{1+r} = p_1 e_1^s + \frac{p_2 e_2^s}{1+r}, \tag{3}$$

$$\text{s. t.} \qquad \bar{e} = e_1^s + e_2^s. \tag{4}$$

The resulting first-order condition, given by

$$[1 + r]p_1 = p_2, \tag{5}$$

is obtained by using (4) in (3) to substitute for e_2^s and subsequently deriving with respect to e_1^s, which gives the marginal net present value of profit. The latter is independent of the choice of e_1^s (and e_2^s) and equates to zero, if market prices satisfy (5), which represents a simple version of the Hotelling rule. Thus, if discounted resource prices of different periods are identical, as stated by (5), the resource extracting firm is indifferent regarding the supply quantity in each period.

Finally, the representative **private household** in each country is the third type of private agent in the model. It obtains utility from consuming in each period and therefore spends her income on the (consumption) good produced by the local firms. The household's preferences are represented by a homothetic lifetime utility function $U(c_{i1}, c_{i2})$ where c_{it} denotes consumption in country i in period t. We assume that c_{i1} are normal goods.

The income of household in period t comprises profit transfers by the local firm π_{it} and a share of $\frac{1}{n}$ of the global resource rent $(\frac{\pi_t^R}{n})$. Moreover, we assume, the household smooths out consumption over time by borrowing debt (providing credit) in period 1, denoted by b_i (a creditor's b_i would be negative), and repaying (receiving) it in period 2. Finally, tax income in period t, given by $T_{it} = \tau_{it} e_{it}$, is recycled as a lump sum transfer to the household. Formally, the household's optimization problem is given by

$$\max_{c_{i1}, c_{i2}, b_i} \quad u = U(c_{i1}, c_{i2}) \tag{6}$$

$$\text{s.t.} \quad c_{i1} = \pi_{i1} + \frac{\pi_1^R}{n} + T_{i1} + b_i, \tag{7}$$

$$c_{i2} = \pi_{i2} + \frac{\pi_2^R}{n} + T_{i2} - b_i[1 + r]. \tag{8}$$

According to (6) - (8) the household in country i maximizes its life-time utility subject to the budget constraints over the two periods. Using (7) and (8) in (6), the problem is reduced to the choice of debt b_i. We obtain the first-order condition given by

$$\frac{U_1}{U_2} = 1 + r, \tag{9}$$

where U_1 and U_2 denote marginal utility of consumption in period 1 and 2 respectively. It states, the marginal rate of intertemporal substitution, given by the left-hand side of (9), should equal the relative price of consumption today vs. consumption tomorrow. Thus, the household will choose b_i so as to adjust its path of consumption in a way that the cost of increasing consumption today, given by the interest rate, just matches the ratio of additional utility today and loss of utility tomorrow.

The description of the private part of the model is completed by the clearing conditions for the consumption good, the resource, and the savings market, i. e.

$$\sum_{k=1}^{n} c_{kt} = \sum_{k=1}^{n} F(e_{kt}), \qquad t = 1, 2 \tag{10}$$

$$\sum_{k=1}^{n} e_{kt} = e_t^s, \qquad t = 1, 2 \tag{11}$$

$$\sum_{k=1}^{n} b_k = 0. \tag{12}$$

These equations state that demand must equal supply on the respective market.[6]

One important aspect mentioned in the introduction was the harmful effect of greenhouse gas emissions on welfare via climate change. We incorporate this into the model by assuming that the use of the resource in production causes environmental damage. Thereby we assume that periodical damages depend on the accumulated stock of emissions in the atmosphere, i. e. damage per period, denoted by d_t for $t = 1, 2$, is given by $d_1 = D(e_1^s)$ and $d_2 = D(e_1^s + e_2^s)$ with $D' > 0$ and $D'' > 0$, where global resource demand is substituted by using (11). Since we also assume that the polluting resource is fully depleted at the end of period 2, life-time damage for the household is simply given by $D(e_1^s)$. This admittedly very simple form of accounting for climate damage helps us to focus on damage from the speed of extraction. For simplicity, welfare in country i is assumed to be additively separable in utility and damage, and is formally given by

$$W_i = U(c_{i1}, c_{i2}) - D(e_1^s). \tag{13}$$

For later purposes, we derive the impact of the policy parameters τ_{i1} and τ_{i2} on the market equilibrium. The latter is described by the private actors' first-order conditions, given by (2), (5) and (9), the resource constraint (4) and the household budgets (7) and (8) as well as the market clearing conditions (11) and (12). Henceforth, we focus on symmetry assuming that countries choose symmetric tax rates $\tau_{it} = \tau_t$. Then, from (2) it follows that $F'(e_{it}) = F_t'$ and $e_{it} = e_t$. And due to (7) - (9) as well as (12) we obtain $b_i = b = 0$, $c_{it} = c_t$ and $U_t(c_{c_i1}, c_{i2}) = U_t$. We find the following comparative static effects of changing today's or tomorrow's carbon tax rate in country i:

$$\frac{\partial r}{\partial \tau_{i1}} > 0, \quad \frac{\partial p_1}{\partial \tau_{i1}} < 0, \quad \frac{\partial p_2}{\partial \tau_{i1}} < 0, \tag{14a}$$

$$\frac{\partial e_{i1}}{\partial \tau_{i1}} < 0, \quad \frac{\partial e_{i2}}{\partial \tau_{i1}} > 0, \quad \frac{\partial e_{j1}}{\partial \tau_{i1}} > 0, \quad \frac{\partial e_{i2}}{\partial \tau_{i1}} = \frac{\partial e_{j2}}{\partial \tau_{i1}} > 0, \quad \frac{\partial e_1^s}{\partial \tau_{i1}} < 0, \tag{14b}$$

$$\frac{\partial r}{\partial \tau_{i2}} < 0, \quad \frac{\partial p_1}{\partial \tau_{i2}} < 0, \quad \frac{\partial p_2}{\partial \tau_{i2}} < 0, \tag{14c}$$

$$\frac{\partial e_{i1}}{\partial \tau_{i2}} = \frac{\partial e_{j1}}{\partial \tau_{i2}} > 0, \quad \frac{\partial e_{i2}}{\partial \tau_{i2}} < 0, \quad \frac{\partial e_{j1}}{\partial \tau_{i2}} > 0, \quad \frac{\partial e_{j2}}{\partial \tau_{i2}} > 0, \quad \frac{\partial e_1^s}{\partial \tau_{i2}} > 0. \tag{14d}$$

[6] Equation (10) is stated merely for the sake of completeness. Due to Walras' law, we can ignore it and normalize the price of the consumption good to unity (see Eichner and Pethig, 2013).

For the derivation see Appendix A. The effects stated in (14a) - (14d) can be explained as follows: Raising the present tax rate, τ_{i1}, increases the gross factor cost per unit in country i, $p_1 + \tau_{i1}$, suppressing demand for the natural resource by the local firm, e_{i1}. The resulting excess supply puts downward pressure on p_1, which in turn has two effects. It induces demand in other jurisdictions, e_{j1}, to increase, since the gross factor cost there falls and at the same time supply, e_1^s, is shifted to the second period due to the Hotelling rule, given by (5). The latter reaction lets p_2 fall, since accommodating additional supply leads to falling marginal productivity in period 2. Finally, the shift of resource supply from period 1 to period 2 leads to less production in period 1 and according to (9) to a rising marginal intertemporal rate of substitution and thus a rising interest rate, r. Raising the future tax rate, τ_{i2}, works into the opposite direction since the distortion of the factor market takes place in period 2.

2.2 Policy Choice

We consider a one-shot Nash game among policy makers, who choose local carbon tax rates for both periods to maximize welfare of the domestic household (13). The optimization problem for the policy maker in country i, who is considering the household's budget constraints (7) and (8) as well as the comparative static effects (14a) - (14d), formally reads

$$\max_{\tau_{i1},\tau_{i2}} \qquad W_i = U\left(c_{i1}\left(\tau_{i1},\tau_{i2}\right), c_{i2}\left(\tau_{i1},\tau_{i2}\right)\right) - D\left(e_1^s\left(\tau_{i1},\tau_{i2}\right)\right), \tag{15}$$

where we denote the market equilibrium variables as functions of the tax rates in country i and suppress the tax rates of other countries due to the Nash conjecture. We limit our analysis to a symmetric equilibrium policy choice, as outlined above. In order to obtain the optimal carbon tax strategy in country i, we take the first-order conditions of (15), which read $\frac{\partial W_i}{\partial \tau_{it}} = 0$ for $t = 1, 2$, use the differentiated household budget constraints, see (76) and (77) in Appendix A (divided by $\mathrm{d}\tau_{it}$), and simplify with the help of the resource extractor's and the households' first-order conditions, given by (5) and (9), which gives

$$\begin{aligned} \frac{\partial W_i}{\partial \tau_{it}} &= U_1 \frac{\partial c_{i1}}{\partial \tau_{it}} + U_2 \frac{\partial c_{i2}}{\partial \tau_{it}} - D' \frac{\partial e_1^s}{\partial \tau_{it}} = 0 \\ \Leftrightarrow \frac{\partial W_i}{\partial \tau_{it}} &= U_1 \tau_1 \tfrac{\partial e_{i1}}{\partial \tau_{it}} + U_2 \tau_2 \tfrac{\partial e_{i2}}{\partial \tau_{it}} - D' \tfrac{\partial e_1^s}{\partial \tau_{it}} = 0, \qquad t = 1, 2. \end{aligned} \tag{16}$$

Then we solve system of two equations given in (16) for τ_1 and τ_2 and obtain

Proposition 1. *The symmetric equilibrium tax rates of the Nash policy game are given* *by*

$$\tau_1^* = \frac{D'}{U_1} \underbrace{\frac{\frac{\partial e_1^s}{\partial \tau_{i1}}\frac{\partial e_{i2}}{\partial \tau_{i2}} - \frac{\partial e_1^s}{\partial \tau_{i2}}\frac{\partial e_{i2}}{\partial \tau_{i1}}}{\frac{\partial e_{i1}}{\partial \tau_{i1}}\frac{\partial e_{i2}}{\partial \tau_{i2}} - \frac{\partial e_{i2}}{\partial \tau_{i1}}\frac{\partial e_{i1}}{\partial \tau_{i2}}}}_{\in]0,1[} > 0, \tag{17}$$

$$\tau_2^* = \frac{D'}{U_2} \underbrace{\frac{\frac{\partial e_1^s}{\partial \tau_{i2}}\frac{\partial e_{i1}}{\partial \tau_{i1}} - \frac{\partial e_1^s}{\partial \tau_{i1}}\frac{\partial e_{i1}}{\partial \tau_{i2}}}{\frac{\partial e_{i1}}{\partial \tau_{i1}}\frac{\partial e_{i2}}{\partial \tau_{i2}} - \frac{\partial e_{i2}}{\partial \tau_{i1}}\frac{\partial e_{i1}}{\partial \tau_{i2}}}}_{\in]-1,0[} < 0. \tag{18}$$

Proof. See Appendix A. ■

The equilibrium taxation strategy, presented in Proposition 1, consists of a positive tax rate in period 1 and a negative tax rate (hence a subsidy) in period 2. The rationale behind this result is to be found in the comparative static effects shown above. By raising the first-period carbon tax, country i is slowing down the emission path $\left(\frac{\partial e_1^s}{\partial \tau_{i1}} < 0\right)$ and therefore reduces environmental damage. On the contrary, the second-period carbon tax has to be lowered to yield an effect in this direction $\left(\frac{\partial e_1^s}{\partial \tau_{i2}} > 0\right)$. The reason for using the carbon tax in both periods instead of one is that τ_{i1} as well as τ_{i2} distort private decisions and that these distortions grow overproportionately with the absolute value of the tax rate. Hence, using both instruments moderately instead of heavily using a carbon tax in only one period reduces the overall distortion.

To explain our findings in more detail, the expressions determining the equilibrium carbon tax rates (17) and (18) may be divided into two terms. The marginal damage to utility ratios, $\frac{D'}{U_1}$ and $\frac{D'}{U_2}$ respectively, highlight the trade-off between the (direct) cost and benefits of the policy, given by the intertemporal shift in consumption and the reduction of environmental damage.

The remaining terms in (17) and (18) represent the effectiveness of the tax rates τ_{i1} and τ_{i2} respectively by relating the change of the tax base, i. e. resource consumption today or in the future, to the speed of extraction. In Appendix A we show that both ratios are less than one in absolute terms. This is driven by the interregional relocation of resource demand (inter-regional leakage), see equations (96) and (97) in Appendix A, which is indicated by $\frac{\partial e_{j1}}{\partial \tau_{i1}} > 0$ and $\frac{\partial e_{j2}}{\partial \tau_{i2}} > 0$ respectively.

Proposition 1 is in line with the literature on optimal carbon taxation, which finds that emission taxation trajectories should flatten the time path of the resource price for the demand side in order to incentivize a shift of fossil fuel demand, and consequently supply, to the future.[7] In the present model, the price path of the resource is increasing at a rate of $1 + r$ due to the Hotelling rule in the absence of policy. However, with equilibrium carbon tax rates the price path for resource users becomes $p_t + \tau_t$, which rises at a rate less than $1 + r$ since $\tau_1^* > 0$ and $\tau_2^* < 0$ according Proposition 1.

[7] See e. g. Dasgupta and Heal (1979), Sinclair (1992), Sinclair (1994), or Sinn (2008).

3 A World with Cap-and-Trade Policy and Local Permit Markets

3.1 Market Equilibrium

We now turn to the assessment of cap-and-trade policies, for which we adapt the model presented above. The volume of emission permits in country i and period t is denoted by $\hat{e}_{it}$ and we assume that all permits are handed out freely to the local firm.[8] Formally, the local firm's maximization problems reads

$$\begin{aligned} \max_{e_{it}} \quad & \pi_{it} = F(e_{it}) - [p_1 + \phi_{it}]\, e_{it} + \phi_{it}\hat{e}_{it}, \\ \text{s.t.} \quad & e_{it} \leq \hat{e}_{it}, \end{aligned} \tag{19}$$

where ϕ_{it} denotes the permit price in country i and period t. The firm's total earnings thus consist of profits from production as well as of pollution permit sales. Its optimization problem is constrained by the emission cap, since in each country there is only one representative firm. Given the assumptions regarding $F(\cdot)$ stated in the previous section, the profit-maximizing firm fully exploits the cap $e_{it} = \hat{e}_{it}$. So, the first-order condition to the problem given by (19) reads

$$F'(e_{it}) = p_t + \phi_{it}. \tag{20}$$

The extraction firm's objective function (3), the resource constraint (4) and its first-order condition (5) carry directly over from the carbon taxation scenario. However, the household's budget constraints are slightly different and read

$$c_{i1} = \pi_{i1} + \frac{\pi_1^R}{n} + b_i, \tag{21}$$

$$c_{i2} = \pi_{i2} + \frac{\pi_2^R}{n} - b_i[1 + r], \tag{22}$$

with the major difference that there are no transfers of public revenue due to free permit allocation, i.e. $T_{i1} = T_{i2} = 0$. Firm profits π_{it} are given by (19) and the revenue of the resource extractor π_t^R is given, as before, by (3). The maximization problem of the household (6) applies here, but is subject to (21) and (22). Since the household perceives income as given, the resulting first-order condition (9) also carries over. And so do the market clearing conditions (10) - (12).

Before we proceed to the derivation of the policy choice, we motivate that policy makers have an interest to set caps in the first, but not in the second period. The reason behind

[8] In the present model, free allocation of permits to firms is equivalent to auctioning and redistributing the permit sales to the household via a lump-sum transfer. The reason is that the household is the sole owner of the local production firm and receives all local permit sales through either scheme, while the firm's decision is not affected by free allocation or auctioning.

this is that permit prices cannot fall below zero in contrast to taxes. Hence, a cap can only be used to yield a reduction of resource use in a given period and country, while taxes may function as an incentive to increase resource consumption in that period when converted into subsidies, see Section 2. In the following, we assess the incentive of country i to introduce a cap either in period 1 or 2 always taking as given that all other countries implement caps only in period 1. So, for the time being, we formulate welfare as a function of the caps in both periods

$$W_i = U\left(c_{i1}\left(\hat{e}_{i1}, \hat{e}_{i2}\right), c_{i2}\left(\hat{e}_{i1}, \hat{e}_{i2}\right)\right) - D\left(e_1^s\left(\hat{e}_{i1}, \hat{e}_{i2}\right)\right), \tag{23}$$

where we again suppress foreign caps due to the Nash conjecture.

3.2 Introduction of a Cap in Period 2

Suppose that country i imposes a cap in period 1 and introduces a cap in period 2, while all other countries $j \neq i$ implement caps only in period 1. Thus we have $e_{it} = \hat{e}_{it}$ for $t = 1, 2$ and $e_{j1} = \hat{e}_{j1}$, while $\phi_{j2} = 0$ since countries $j \neq i$ implement no cap in period 2. The market equilibrium is described by (4), (5), (9), (12) and (20) for $t = 1$, as well as

$$F_2'(e_{i2}) = p_2 + \phi_{i2}, \tag{24}$$

$$F_2'(e_{j2}) = p_2, \tag{25}$$

$$\sum_{k=1}^{n} \hat{e}_{k1} = e_1^s, \tag{26}$$

$$\sum_{j \neq i}^{n} e_{j2} + \hat{e}_{i2} = e_2^s. \tag{27}$$

In order to assess the marginal effect of $\hat{e}_{i2}$ on welfare in country i, we derive its comparative static effects of $\hat{e}_{i2}$ on the time path of extraction and domestic consumption in each period. Therefore, we differentiate (26), where $\mathrm{d}\hat{e}_{i1} = \mathrm{d}\hat{e}_{j1} = 0$ due to the Nash conjecture, and find

$$\frac{\partial e_1^s}{\partial \hat{e}_{i2}} = 0, \tag{28}$$

and due to our assumption of inelastic total resource supply, see (4), we obtain also[9]

$$\frac{\partial e_2^s}{\partial \hat{e}_{i2}} = 0. \tag{29}$$

These findings indicate that, given all countries employ binding caps in period 1, the policy maker in country does not exert any effect on the time structure of resource supply.

[9]Equation (29) is obtained by totally differentiating (4) and using (28).

The comparative static effects on consumption are obtained by differentiating the budget constraints (21) and (22). There we get

$$\frac{\partial c_{i1}}{\partial \hat{e}_{i2}} = \frac{\partial b_i}{\partial \hat{e}_{i2}}, \tag{30}$$

$$\frac{\partial c_{i2}}{\partial \hat{e}_{i2}} = \phi_{i2} - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i2}}, \tag{31}$$

see Appendix B. The net effect of $\hat{e}_{i2}$ on profit income and the lump sum transfer amounts to ϕ_{i2} in period 2, while period 1 all partial effects on profit income offset each other. According to (31), lowering the number of permits reduce income by the value that these permits have. This decrease in the transfer of permit revenues can be interpreted as a loss in economic surplus, since the permit price is equal to the difference between the marginal product of the resource in production and its factor price, see (24). Due a change in income in period 2, the household may adjust demand for debt, which affects consumption in both periods. However, introducing $\hat{e}_{i2}$ means that the comparative static effects are evaluated at marginally binding cap level ($\phi_{i2} = 0$), so that the net effect on income in period 2 disappears.

And when we finally look at welfare, deriving (23) with respect to $\hat{e}_{i2}$ and considering (28), (30) and (31) we find that the marginal effect is zero

$$\frac{\partial W_i}{\partial \hat{e}_{i2}} = 0, \tag{32}$$

see Appendix B for the derivation. The rationale behind this result is twofold. Firstly, the change in household debt has no effect on life-time utility due to an undistorted inter-household capital market – $\frac{\partial b_i}{\partial \hat{e}_{i2}}$ cancels out. And secondly, environmental damage does not change since the extraction in period 1 is not affected by the cap in period 2 according to (28).

3.3 Tightening the Cap in Period 1 Beyond the Marginally Binding Level

Now suppose that all countries implement a marginally binding cap in period 1 and no country imposes a cap in the second period, i. e. $e_{k1} = \hat{e}_{k1}$ and $\phi_{k2} = \phi_{k2} = 0$ for $k = i, j$. The market equilibrium here is identical to the one described for the assessment of the introduction of the second-period cap, only that we adapt (24) - (27) to account for the complete absence of cap-and-trade policy period 2, which gives

$$\sum_{k=1}^{n} \hat{e}_{k1} = e_1^s, \tag{33}$$

$$F_2'(e_{k2}) = p_2, \quad \text{for } k = i, j, \tag{34}$$

while market clearing condition for the resource in $t = 2$ is given by (11). The comparative static effects of changing the cap in period 1 differ substantially from those induced by changing $\hat{e}_{i2}$. Differentiating (33) with respect to $\hat{e}_{i1}$ we obtain

$$\frac{\partial e_1^s}{\partial \hat{e}_{i1}} = 1, \tag{35}$$

which we use together with the differentiated resource constraint (4) to receive

$$\frac{\partial e_2^s}{\partial \hat{e}_{i1}} = -1. \tag{36}$$

Equations (35) and (36) state that tightening the cap of country i in period 1 shifts resource supply in exact proportion from period 1 to period 2. Thus, the policy maker can effectively induce a postponement of resource extraction by tightening $\hat{e}_{i1}$ beyond the marginally binding level. Moreover, she is able to do so without causing carbon leakage – in contrast to the setting with carbon taxes.

The effect of $\hat{e}_{i1}$ on consumption is also different from the case of introducing $\hat{e}_{i2}$. This can be seen by differentiating (21) and (22), for which we obtain

$$\frac{\partial c_{i1}}{\partial \hat{e}_{i1}} = \phi_{i1} + \frac{p_1}{n} + \frac{\partial b_i}{\partial \hat{e}_{i1}}, \tag{37}$$

$$\frac{\partial c_{i2}}{\partial \hat{e}_{i1}} = -\frac{p_2}{n} - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i1}}. \tag{38}$$

See Appendix B for the derivation. The net effect on income induced by a reduction in $\hat{e}_{i1}$ consists of lower permit revenues and lower resource rents in period 1, while the latter increase in period 2, which can be seen in (37) and (38) by setting $\mathrm{d}\hat{e}_{i1} < 0$. The former effect is due to the reduction of permits itself, while the latter is owed to the shift of resource supply from period 1 to period 2. These changes on income again motivate changes in debt demand by the household. However, given that first-period caps are just marginally binding, we have $\phi_{i1} = 0$ in (37).

When looking at the overall effect of $\hat{e}_{i1}$ on welfare in country i, we find that a tightening beyond the marginally binding level increases welfare, i. e.

$$\frac{\partial W_i}{\partial \hat{e}_{i1}} = -D' < 0, \tag{39}$$

which we obtain by differentiating (23) with respect to $\hat{e}_{i1}$ and considering (35), (37) and (38). See again Appendix B for the derivation. Since reducing $\hat{e}_{i1}$ shifts extraction to the future, environmental damage decreases and therefore welfare increases. At the same time, the changes in consumption do not affect life-time utility again due to the undistorted intertemporal market.[10] From (32) and (39) we infer

Lemma 1. *Given environmental damage is stock-depend and total extraction is exogenously given, local policy makers implement cap-and-trade policy only in the first of two periods.*

[10]The changes in debt demand and the alteration of periodical extraction profits cancel out, since the resource extractor's discount rate, the marginal intertemporal rate of substitution by the household and the interest rate at the capital market all coincide in the market equilibrium.

3.4 Policy Choice

Based on Lemma 1, we consider a Nash game among policy makers who each maximize welfare of their local household, given by (23), setting a cap on emissions in period 1 only. Accounting for the fact that the use of the cap is limited to period 1 in (23), the maximization problem of the policy maker in country i reads

$$\max_{\hat{e}_{i1}} \quad W_i = U\left(c_{i1}\left(\hat{e}_{i1}\right), c_{i2}\left(\hat{e}_{i1}\right)\right) - D\left(e_1^s\left(\hat{e}_{i1}\right)\right). \tag{40}$$

In solving (40), the policy maker considers the comparative static effects given by (35) - (38), while $\phi_{i1} \geq 0$, since the policy choice could be a strictly binding cap.[11]

The first-order condition of (40) is given by $\frac{\partial W_i}{\partial \hat{e}_{i1}} = 0$, which we simplify with the help of (35), (37) and (38) and obtain[12]

$$\frac{\partial W_i}{\partial \hat{e}_{i1}} = U_1 \phi_{i1} - D' = 0. \tag{41}$$

The net effects of the policy instrument on income as well as on debt demand, see (37) and (38), offset each other over the two periods – except for the change in permit revenues. Thinking in terms of tightening the cap ($\mathrm{d}\hat{e}_{i1} < 0$), the decrease in permit revenues represents the marginal cost of the policy ($U_1\phi_{i1}$). On the other hand, the marginal benefit consists in the reduction of environmental damage by diminishing first-period resource consumption, see (35). For the policy equilibrium, we again consider symmetry, i. e. $\hat{e}_{i1}^* = \hat{e}_1^*$ implying $\phi_{i1}^* = \phi_1^*$.

Proposition 2. *Suppose that policy makers only implement a cap policy in period 1 and that permit markets are local. The symmetric Nash equilibrium exhibits a permit price*

$$\phi_1^* = \frac{D'}{U_1} > 0, \tag{42}$$

while, following Lemma 1, permit prices in period 2 are implicit and equal to zero

$$\phi_2^* = 0. \tag{43}$$

Proof. See Appendix B. ■

According to Proposition 2, policy makers restrict the use of the polluting resource in period 1 to an extent, where the marginal utility loss from the decreasing economic surplus just equals the marginal benefit of reduced environmental damage.[13]

[11] The structure of the market equilibrium is identical to the one presented above, where we study the effect of tightening a marginally binding cap in period 1.
[12] See Appendix B for the derivation.
[13] Slightly rearrange (42) to obtain $U_1\phi_1^* = D'$.

4 A World with Cap-and-Trade Policy and Linked Permit Markets

Finally, we turn to the extension regarding the cap-and-trade scenario. Suppose countries create a single market for emission permits with a global permit price φ_t, where the sum of all permits, which we denote by $\check{e}_{it}$, constitutes total supply. Formally, the single permit market implies $\sum_{k=1}^{n} e_{kt} \leq \sum_{k=1}^{n} \check{e}_{kt}$. The decision on permit levels is assumed to remain with the local policy makers, which is why we keep the country index for local permit supplies $\check{e}_{it}$. Additionally, we assume that a share α of locally determined permits is auctioned by a central authority, which then redistributes total revenues evenly among all countries. Local governments then pass on this payment to their domestic households. Thus, in country i the household receives $T_{it} = \frac{\alpha}{n}\varphi_t \sum_{k=1}^{n} \check{e}_{kt}$, while the firm obtains $[1-\alpha]\varphi_t \check{e}_{it}$.

Therefore, we adapt the model with cap-and-trade policy presented in Section 3. For the profit maximization problem of the firm in country i, given by (19), we have here

$$\max_{e_{it}} \qquad \pi_{it} = F(e_{it}) - [p_t + \varphi_t]\, e_{it} + [1-\alpha]\varphi_t \check{e}_{it}, \tag{44}$$

from which we obtain the first-order condition, which reads

$$F'(e_{it}) = p_t + \varphi_t. \tag{45}$$

In contrast to the case of local permit markets, demand of the local production firm for the resource e_{i1} is not constrained by the quantity of domestic permits $\check{e}_{i1}$. However, taking the characteristics of the production function ($F_t' > 0, F_t'' < 0,\ F_t'(e=0) \to \infty$) we argue that the firms of all countries together fully exploit the sum of certificates in each period, which gives

$$\sum_{k=1}^{n} e_{kt} = \sum_{k=1}^{n} \check{e}_{kt}. \tag{46}$$

Concerning the household budget constraints (21) and (22), firm profits π_{it} are given by (44) and we reintroduce government transfers $T_{it} = \frac{\alpha}{n}\varphi_t \sum_{k=1}^{n} \check{e}_{kt}$, while the profit of the resource-extracting firm is unchanged and given by (3). As outlined in the previous section, the household's optimization problem, given by (6) together with the first-order condition, given by (9), carries over from the other scenarios. Finally, the market clearing conditions (11) and (12), as well as the resource constraint (4) apply here.

Now we turn to the policy makers. In Appendix C we show that these have an incentive to tighten their permit supply below the marginally binding level only in period 1. Therefore, we assume the cap-and-trade policy is implemented only in period 1 under the linked-permit-market regime, just like in the local permit market regime. So, the local firm's optimization problem in period 2 carries over from Section 3.3 and in the household budget in period 2 exhibits $T_{i2} = 0$. Thus, the market equilibrium is given by (4), (5), (9), (12), as well as (45) and (46) for $t = 1$, or (11) and (34) for $t = 2$.

The comparative static effects of changing $\check{e}_{i1}$ on the extraction path of the resource as well as on household consumption are derived in Appendix C. For the effect on fossil fuel supply in period 1 we find

$$\frac{\partial e_1^s}{\partial \check{e}_{i1}} = 1, \tag{47}$$

which resembles (35). The comparative static effect is the same, since in both cases, i. e. local and linked permit markets, the sum of permit levels constrains global fossil fuel supply in period 1 and a change of $\hat{e}_{i1}$ or $\check{e}_{i1}$ defines the loosening or tightening of this constraint. Also, the effects on consumption in both periods, given by

$$\frac{\partial c_{i1}}{\partial \check{e}_{i1}} = \left[1 - \alpha + \frac{\alpha}{n}\right] \varphi_1 + \frac{p_1}{n} + \frac{\partial b_i}{\partial \check{e}_{i1}}, \tag{48}$$

$$\frac{\partial c_{i2}}{\partial \check{e}_{i1}} = -\frac{p_2}{n} - [1 + r] \frac{\partial b_i}{\partial \check{e}_{i1}}, \tag{49}$$

are nearly identical with one exception. The effect on c_{i1} is different from the case of local permit markets due to the redistribution mechanism, see the first term on the right hand side of (48). If all permits are handed out freely to the firms, i. e. $\alpha = 0$, then we are back to the case of local markets. The reduction of permit revenues for the household in country i amounts to the permit price φ_1, i.e. the value of the marginal permits taken off the market. However, if all permits are auctioned and centrally redistributed, i. e. $\alpha = 1$, a cap tightening in country i affects the household there through a marginal loss of only $\frac{1}{n}\varphi_1$. This is so, because the total reduction of permit revenues, which follows from a reduction of $\check{e}_{i1}$, is shared out among the households of all n countries.

We now turn to the policy makers' problem. In line with the scenarios presented above, we assume, policy makers determine the amount of permits $\check{e}_{i1}$ to maximize local welfare in a Nash game, considering the comparative static effects (47), (48) and (49). Formally, the policy problem reads

$$\max_{\check{e}_{i1}} \quad W_i = U\left(c_{i1}\left(\check{e}_{i1}\right), c_{i2}\left(\check{e}_{i1}\right)\right) - D\left(e_1^s\left(\check{e}_{i1}\right)\right), \tag{50}$$

and the corresponding first-order condition, given by $\frac{\partial W_i}{\partial \check{e}_{i1}} = 0$, simplifies to

$$\frac{\partial W_i}{\partial \check{e}_{i1}} = \left[1 - \alpha + \frac{\alpha}{n}\right] U_1 \varphi_1 - D' = 0, \tag{51}$$

where we used (47), (48) and (49). See Appendix C for the derivation. The optimal policy choice following from (51) is presented in the following Proposition.

Proposition 3. *Suppose that policy makers only implement cap-and-trade policy in period 1 and that permits are traded on a global market. The symmetric Nash equilibrium exhibits a global permit price in period 1*

$$\varphi_1^*|_{\alpha=0} = \frac{D'}{U_1} > 0, \tag{52}$$

or

$$\varphi_1^*|_{\alpha=1} = \frac{nD'}{U_1} > 0, \tag{53}$$

depending on the value of α, while the global permit price in period 2 is implicit and equal to zero

$$\varphi_2^*|_{\alpha\in[0,1]} = 0. \tag{54}$$

Proof. Statements (52) and (53) are obtained directly from (51). ■

Comparing Propositions 2 and 3, we find that $\phi_1^* = \varphi_1^*|_{\alpha=0}$. Thus, without any central auctioning the equilibrium permit prices are identical in the local-permit-market and the global-permit-market scenarios. The rationale behind this finding is that marginal costs of tightening the first-period caps are identical,[14] since redistributed revenues T_{i1} are structurally the same in both scenarios. These depend on domestic permits only as well as on the permit price, which is identical in both cases, given that $\check{e}_1 = \hat{e}_1$. However, the introduction of central redistribution to equal shares makes the difference. Domestic permit revenue only makes up a share of $\frac{1}{n}$ of T_{i1}. This in turn lowers the marginal cost of tightening the domestic cap exactly by that fraction.

5 Welfare Analysis

Having derived the policy equilibria for the carbon taxation scenario as well as for the cap-and-trade scenarios we proceed to the welfare analysis and the ranking of the policies. We begin by deriving the first-best policy choice, which defines the benchmark for evaluating the decentral policy equilibrium in each scenario. To this end we assume that local policy makers act cooperatively, i. e. they take into account the effects of their policy on domestic and foreign welfare. We will derive the optimal cooperative carbon taxation strategy, but the same could be done with the either permit instrument ($\hat{e}_{i1}$ or $\check{e}_{i1}$). The local policy makers' problem under cooperation is analogous to that under non-cooperative carbon taxation policy, which is given by (15). Yet, the cooperatively acting policy maker maximizes sum of all countries' welfare levels. We therefore obtain the maximization problem

$$\max_{\tau_{i1},\tau_{i2}} \quad \sum_{k=1}^{n} W_k = \sum_{k=1}^{n} U\left(c_{k1}(\tau_{i1},\tau_{i2}), c_{k2}(\tau_{i1},\tau_{i2})\right) - nD\left(e_1^s(\tau_{i1},\tau_{i2})\right). \tag{55}$$

Due to the symmetry of countries we again consider a symmetric policy choice, yielding identical marginal utility across countries $U_{it} = U_{jt} = U_t$. The first-order condition for country i's policy maker regarding the tax rate τ in period $t = 1, 2$ thus reads

$$\sum_{k=1}^{n} \frac{\partial W_k}{\partial \tau_{it}} = U_1 \sum_{k=1}^{n} \frac{\partial c_{k1}}{\partial \tau_{it}} + U_2 \sum_{k=1}^{n} \frac{\partial c_{k2}}{\partial \tau_{it}} - nD' \frac{\partial e_1^s}{\partial \tau_{it}} = 0 \quad \text{for } t = 1, 2. \tag{56}$$

[14]Set $\alpha = 0$ in (51) and compare to (41).

The notion of cooperatively chosen domestic policies as well as symmetric policy and market equilibria allows us to employ the comparative statics derived for carbon taxes in Section 2 and Appendix A. For the sum of changes in consumption we obtain

$$\sum_{k=1}^{n} \frac{\partial c_{kz}}{\partial \tau_{it}} = \frac{\partial c_{iz}}{\partial \tau_{it}} + [n-1]\frac{\partial c_{jz}}{\partial \tau_{it}} = [\tau_z + p_z]\frac{\partial e_z^s}{\partial \tau_{it}}, \text{ for } t, z = \{1, 2\}, \tag{57}$$

which we derive in detail in Appendix D. We then use (57) in (56) and simplify with the help of the differentiated resource constraint (4) to obtain

$$\sum_{k=1}^{n} \frac{\partial W_k}{\partial \tau_{it}} = \big[U_1[\tau_1 + p_1] - U_2[\tau_2 + p_2] - nD'\big]\frac{\partial e_1^s}{\partial \tau_{it}} = 0, \text{ for } t = 1, 2. \tag{58}$$

Since we have $\frac{\partial e_1^s}{\partial \tau_{it}} \neq 0$, see Appendix A, the term in square brackets gives the solution to the problem. However, this term is identical for both first-order conditions, which indicates that we have one degree of freedom. Put differently, the solution is a linear combination of carbon tax rates in periods 1 and 2. Using the first-order conditions of the resource extractor (5) and the household (9) to simplify, we obtain

Proposition 4. *Suppose each policy maker considers external effects of its local carbon tax on other countries' welfare. Then the optimal choice of carbon tax rates is given by the following linear combination*

$$\tau_1^{fb} - \frac{\tau_2^{fb}}{1+r} = n\frac{D'}{U_1} > 0. \tag{59}$$

Proof. See Appendix D. ■

Proposition 4 states that the differential of discounted carbon taxes has to equal the sum of all countries' marginal environmental damage. Given symmetry, global marginal welfare is affected only by the impact of the policy instrument on the time path of resource supply, which in turn determines environmental damage. Moreover, the policy maker in country i considers the environmental benefits of its policy experienced in other countries. Therefore, the term on the right-hand side of (59) exhibits the factor n, denoting the number of countries. Interregional leakage, on the other hand, is internalized through cooperation and disappears from the optimality condition altogether, since the outflow of resource demand in country i is exactly offset by the inflow in the remaining countries $j \neq i$. This is owed to the inelastic supply of the resource as well as to symmetry.

We now turn to the welfare comparison of the policy equilibria of the scenarios presented above, see Propositions 1 - 3. Let us therefore introduce the notion of a "carbon fee", denoted by θ_t, as a placeholder for the carbon tax rate τ_t, the local permit price ϕ_{it} or the global permit price φ_t, since each acts as an instrument to price the emission content of the resource. Next to that, we need an indication of the emission quantities associated with specific policy equilibria, and how this relates to each country's welfare. While we cannot solve for the emission quantities themselves, we can show that there exists a strictly monotonic relation between the *steepness* of the carbon fee trajectories (henceforth *differential of discounted carbon fees*) and the respective extraction in period 1. For symmetric allocations, we derive a relation between extraction in period 1 and the level of welfare.

Lemma 2. *Given symmetric policy choices and defining the differential of discounted carbon fees as* $\Delta(\theta_1, \theta_2) := \theta_1 - \frac{\theta_2}{1+r}$ *with* $\theta_t \in [\tau_{it}, \phi_{it}, \varphi_t]$ *the following holds:*

1. $\Delta(\theta_1, \theta_2)$ *is a decreasing function in first-period emissions* $e_1 = e_1^s/n$ *and*

2. *each country's welfare* $W_i(\theta_1, \theta_2)$ *is a single-peaked function of per country early emissions* $e_1 = e_1^s/n$.

Proof. See Appendix D. ∎

Lemma 2 serves to compare the policy equilibrium under the cap-and-trade scenario with linked markets (Proposition 3) to the one under cooperative policy (Proposition 4). The results are summarized in

Proposition 5. *The decentral policy equilibrium in the scenario with cap-and-trade policies, linked permit markets and full redistribution of permit sale revenues (*$\alpha = 1$*) yields the same carbon fee differentials and welfare levels as the first-best policy choice, i. e.*

$$\Delta\left(\tau_1^{fb}, \tau_2^{fb}\right) = \Delta\left(\varphi_1^*|_{\alpha=1}, \varphi_2^*|_{\alpha=1}\right) = n\frac{D'}{U_{c_1}} \tag{60}$$

$$W\left(\tau_1^{fb}, \tau_1^{fb}\right) = W\left(\varphi_1^*|_{\alpha=1}, \varphi_2^*|_{\alpha=1}\right) \tag{61}$$

Proof. Take $\varphi_1^*|_{\alpha=1}$ and $\varphi_2^*|_{\alpha=1}$ from (53) and (54) and compute $\Delta\left(\varphi_1^*|_{\alpha=1}, \varphi_2^*|_{\alpha=1}\right)$. Together with Proposition 4 this gives (60). Then by Lemma 2 and (60) we obtain (61). ∎

Proposition 5 states that equilibrium cap-and-trade policy with linked markets and full international redistribution of permit revenues is efficient. To see why this is the case, we take a look at the externalities country i inflicts on other countries $j \neq i$. Taking the derivative of W_j with respect to $\check{e}_{i1}$ gives[15]

$$\frac{\partial W_j}{\partial \check{e}_{i1}} = \underbrace{\frac{1}{n} U_1 \varphi_1(\check{e}_1^*)}_{RE_{ij}(+)} \underbrace{-D'}_{EE_{ij}(-)} = 0. \tag{62}$$

[15]To obtain (62) we set $\alpha = 1$ in (158) in Appendix E.

In (62), the term denoted by RE_{ij} refers to the redistribution externality and captures the effect of a change of $\check{e}_{i1}$ on the share of global permit revenues transferred to country j. Given that country i loosens its cap, country j experiences a positive effect through increasing transfers from central auctioning revenues. At the same time, the loosing of $\check{e}_{i1}$ lets environmental damage in country j increase (EE_{ij} – environmental externality). An evaluation of (62) at the policy equilibrium shows that external effects exactly offset each other.[16] Therefore, the policy equilibrium in the scenario of cap-and-trade with linked markets and auctioning yields an efficient outcome.

Now we turn to the remaining policy scenarios and the respective equilibria. With the help of Lemma 2 we can rank these with regard to the steepness of their associated emission paths. The results are contained in

Proposition 6. *The differentials of discounted carbon fees of the policy equilibria in carbon taxes (τ^*), local (ϕ^*) and linked permit markets (φ^*) relate to each other as follows:*

$$\Delta(\tau_1^*, \tau_2^*) < \Delta\left(\phi_1^*, \phi_2^*\right) = \Delta\left(\varphi_1^*|_{\alpha=0}, \varphi_2^*|_{\alpha=0}\right) < \Delta\left(\varphi_1^*|_{\alpha=1}, \varphi_2^*|_{\alpha=1}\right), \tag{63}$$

where $\Delta(\tau_1^*, \tau_2^*) = \mathfrak{T}\frac{D'}{U_{c_1}}$ *with* $0 < \mathfrak{T} < 1$, $\Delta\left(\phi_1^*, \phi_2^*\right) = \Delta\left(\varphi_1^*|_{\alpha=0}, \varphi_2^*|_{\alpha=0}\right) = \frac{D'}{U_{c_1}}$ *and* $\Delta\left(\varphi_1^*|_{\alpha=1}, \varphi_2^*|_{\alpha=1}\right) = n\frac{D'}{U_{c_1}}$. *The relations of associated first-period emissions are*

$$e_1^s(\tau_1^*, \tau_2^*) > e_1^s\left(\phi_1^*, \phi_2^*\right) = e_1^s\left(\varphi_1^*|_{\alpha=1}, \varphi_2^*|_{\alpha=1}\right) > e_1^s\left(\varphi_1^*|_{\alpha=1}, \varphi_2^*|_{\alpha=1}\right). \tag{64}$$

Proof. See Lemma 2 and Appendix D. ■

Proposition 6 states that the differential of discounted carbon fees is lowest under carbon taxation. It is second highest under cap-and-trade policy either with local markets or with linked markets and free allocation. Based on the statement of Proposition 5 the differentials of discounted carbon fees of these three scenarios are suboptimally low. Consequently this is reflected in the comparison of equilibrium welfare levels of across scenarios.

Proposition 7. *The cap-and-trade policy equilibrium with auctioning and redistribution ($\alpha = 1$) yields the highest welfare level due to efficiency. The policy equilibrium in the scenarios of cap-and-trade policy with local permit markets and with linked markets and free allocation ($\alpha = 0$) yield identical suboptimal welfare levels. The policy equilibrium in the scenario of carbon taxation yields the lowest welfare level compared to all other scenarios.*

$$W\left(\varphi_1^*|_{\alpha=1}, \varphi_2^*|_{\alpha=1}\right) > W\left(\varphi_1^*|_{\alpha=0}, \varphi_2^*|_{\alpha=0}\right) = W\left(\phi_1^*, \phi_2^*\right) > W\left(\tau_1^*, \tau_2^*\right). \tag{65}$$

Proof. See Propositions 4 and 6 as well as Lemma 2. ■

[16]Using (53) in (62) gives $\frac{\partial W_j}{\partial \check{e}_{i1}} = 0$.

This proposition concludes our normative analysis. The finding that welfare is highest in the equilibrium of cap-and-trade policy with linked permit markets and full actioning directly follows from Proposition 5. Second highest welfare is found in the remaining cap-and-trade scenarios (linked permit markets with free allocation and local permit markets). In both cases policy equilibria yield the same level of welfare since the differentials of their discounted carbon fees are equal and they thus yield the same extraction path. Another way to explain equal welfare levels, but also inefficiency, is to look at prevailing policy externalities. In Appendix E we derive for both scenarios the external effect of country i's permit supply on another country j's welfare. The net external effects in both scenarios, which read[17]

$$\frac{\partial W_j}{\partial \hat{e}_{i1}} = \left.\frac{\partial W_j}{\partial \check{e}_{i1}}\right|_{\alpha=0} = \underbrace{-D' \cdot 1}_{EE_{ij}(-)} < 0. \tag{66}$$

Equation (66) reveals that it is the environmental externality causing this effect (EE_{ij}). If country i chooses a marginally stricter policy ($\mathrm{d}\hat{e}_{i1}$ or $\mathrm{d}\check{e}_{i1} < 0$), it inflicts a positive externality on country j through the reduction of environmental damage. The presence of this externality leads to an inefficient equilibrium.

It is also revealing to take a look at the presence of externalities in the carbon taxation scenario, which ranks lowest in equilibrium welfare. In Appendix E we derive the following expressions for the external effects of country i's tax policy on country j's welfare level

$$\frac{\partial W_j}{\partial \tau_{i1}} = \underbrace{U_1 \tau_1^* \frac{\partial e_{j1}}{\partial \tau_{i1}} + U_2 \tau_2^* \frac{\partial e_{j2}}{\partial \tau_{i1}}}_{LE_{ij}(+)} \underbrace{-D' \frac{\partial e_1^s}{\partial \tau_{it}}}_{EE_{ij}(+)} > 0, \tag{67}$$

$$\frac{\partial W_j}{\partial \tau_{i2}} = \underbrace{U_1 \tau_1^* \frac{\partial e_{j1}}{\partial \tau_{i2}} + U_2 \tau_2^* \frac{\partial e_{j2}}{\partial \tau_{i2}}}_{LE_{ij}(-)} \underbrace{-D' \frac{\partial e_1^s}{\partial \tau_{it}}}_{EE_{ij}(-)} < 0. \tag{68}$$

These reveal that carbon taxation induces two types of externalities: the leakage externality (LE_{ij}) and the environmental externality (EE_{ij}). To read (68) correctly recall that $\mathrm{d}\tau_{i2} < 0$ represent a "tightening" of carbon taxation (increasing the discounted carbon fee differential). So, tightening carbon taxation either in period 1 or 2 in country i inflicts positive externalities on country j at the policy equilibrium. The leakage externality is positive since the relocation of resource use increases net output across the two periods. The environmental externality follows the same logic as in the other policy scenarios. In the end, the fact that the leakage externality adds to the environmental externality, which is present in all scenarios, gives an intuition why carbon taxation yields lower efficiency than all analyzed cases of cap-and-trade policies.

[17] See (153) as well as (158) with $\alpha = 0$ in Appendix E.

6 Conclusion

We derived non-cooperative equilibria of symmetric, climate policy setting jurisdictions and established a welfare ranking of different policy regimes. We have shown that cap-and-trade schemes are superior to carbon taxation, due to their greater effectiveness in limiting emissions. This is due to the fact that in a setting of binding cap levels throughout the world, carbon leakage can be ruled out. Furthermore, efficient emission allocation can be implemented through decentral decision making, if all jurisdictions' permit markets are linked and auctioning revenues are distributed evenly. This result is mainly driven by the effect that the environmental externality is exactly offset by a redistribution externality, which induces each country to choose a lower permission level, since part of the loss in revenues is experienced by other countries.

The development of the recent years, where cap-and-trade policies have been put into practice in an increasing number of world regions,[18] could – if it were to continue – contribute to lower leakage considerably as opposed to the spreading of price instrument regimes. Our model indicates that this could feed back into more stringent policy choices.

With respect to linking of permit markets a real world example can be found in the first phase 2005-2007 of EU emission trading scheme (EU ETS), where national permit levels were determined decentrally. Besides having a single permit market, EU member states decided individually on the level of their national permit levels. In this first phase however, most permits were freely allocated and cap levels where not enforced strictly, see Ellerman et al. (2016).

While the EU ETS determines the cap level centrally since the start of phase 2 in 2008 and the share of auctioned permits increases continuously; for other potential linking initiatives such as between the EU, China, Korea, or California central decision making on cap levels remains much further down along the road. So, our analysis suggests to push for (at least some) centralized permit auctioning, especially if countries are very similar. So the framework of decentrally determined permit levels with a single permit market could remain relevant.

There are some caveats to our analysis. We assume that the total given stock of a single homogeneous resource is exhausted. However, climate research shows that it is certainly not worthwhile to extract and burn all fossil fuels, see Stern (2007). So we refer to a classic, rather scarce type of fossil fuel, say crude oil, and abstract from interaction with other types of fuel, including renewables. Our case can be understood as an extreme one, to show the effects owing to scarcity and speed of extraction. And last but not least we don't explore the incentive to implement the redistribution system. Countries could anticipate the externality and not agree to such a system in the first place. Other limitations are the homogeneity among actors and jurisdictions, and the absence of production factors other than fuels.

[18] See Schmalensee and Stavins (2017).

References

Barrett, S. (1994). Self-enforcing international environmental agreements. *Oxford Economic Papers 46*, 878–894.

Carbone, J. C., C. Helm, and T. F. Rutherford (2009). The case for international emission trade in the absence of cooperative climate policy. *Journal of Environmental Economics and Management 58*(3), 266–280.

Chen, X. and A. Woodland (2013). International trade and climate change. *International Tax and Public Finance 20*(3), 381–413.

Cramton, P., A. Ockenfels, and J. Tirole (2017). Policy brief – translating the collective climate goal into a common commitment. *Review of Environmental Economics and Policy 11*(1), 165–171.

Cropper, M. L. and W. E. Oates (1992). Environmental economics: a survey. *Journal of Economic Literature 30*(2), 675–740.

Dasgupta, P. and G. Heal (1979). *Economic theory and exhaustible resources*. Cambridge: Cambridge University Press.

Eichner, T. and R. Pethig (2013). Flattening the carbon extraction path in unilateral cost-effective action. *Journal of Environmental Economics and Management 66*(2), 185–201.

Eichner, T. and R. Pethig (2015). Self-enforcing international environmental agreements and trade: taxes versus caps. *Oxford Economic Papers 67*(4), 897–917.

Ellerman, A. D., C. Marcantonini, and A. Zaklan (2016). The european union emissions trading system: ten years and counting. *Review of Environmental Economics and Policy 10*(1), 89–107.

Flachsland, C., R. Marschinski, and O. Edenhofer (2009). To link or not to link: benefits and disadvantages of linking cap-and-trade systems. *Climate Policy 9*(4), 358–372.

Fouquet, R. (2010). The slow search for solutions: lessons from historical energy transitions by sector and service. *Energy Policy 38*(11), 6586–6596.

Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica 82*(1), 41–88.

Goulder, L. H. and A. R. Schein (2013). Carbon taxes versus cap and trade: a critical review. *Climate Change Economics 4*(03), 1350010.

Haites, E. (2018). Carbon taxes and greenhouse gas emissions trading systems: what have we learned? *Climate Policy 8*, 955–966.

Hoel, M. (2005). The triple inefficiency of uncoordinated environmental policies. *Scandinavian Journal of Economics 107*(1), 157–173.

Hoel, M. and S. Kverndokk (1996). Depletion of fossil fuels and the impacts of global warming. *Resource and Energy Economics 18*(2), 115–136.

Höök, M. and X. Tang (2013). Depletion of fossil fuels and anthropogenic climate change – A review. *Energy Policy 52*, 797–809.

Iacobuta, G., N. K. Dubash, P. Upadhyaya, M. Deribe, and N. Höhne (2018). National climate change mitigation legislation, strategy and targets: a global update. *Climate Policy*, 1–19.

IPCC (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kiyono, K. and J. Ishikawa (2013). Environmental management policy under international carbon leakage. *International Economic Review 54*(3), 1057–1083.

Krishna, K. (2011). Limiting emissions and trade: some basic ideas. In *The Design and Implementation of US Climate Policy*, pp. 53–61. University of Chicago Press.

Narassimhan, E., K. S. Gallagher, S. Koester, and J. R. Alejo (2018). Carbon pricing in practice: a review of existing emissions trading systems. *Climate Policy*, 1–25.

Schmalensee, R. and R. N. Stavins (2017). Lessons learned from three decades of experience with cap and trade. *Review of Environmental Economics and Policy 11*(1), 59–79.

Shafiee, S. and E. Topal (2009). When will fossil fuel reserves be diminished? *Energy Policy 37*(1), 181–189.

Sim, S.-G. and H.-C. Lin (2018). Competitive dominance of emission trading over pigouvian taxation in a globalized economy. *Economics Letters 163*, 158–161.

Sinclair, P. J. N. (1992). High does nothing, and rising is worse: carbon taxes should keep declining to cut harmful emissions. *The Manchester School LX*, 41–52.

Sinclair, P. J. N. (1994). On the optimum trend of fossil fuel taxation. *Oxford Economic Papers 46*, 869–877.

Sinn, H.-W. (2008). Public policies against global warming: a supply side approach. *International Tax and Public Finance 15*(4), 360–394.

Stern, N. H. (2007). *The economics of climate change: The Stern review.* Cambridge University Press.

Tahvonen, O. (1995). Dynamics of pollution control when damage is sensitive to the rate of pollution accumulation. *Environmental and Resource Economics 5*(1), 9–27.

Tsakiris, N., P. Hatzipanayotou, and M. S. Michael (2017). Welfare ranking of environmental policies in the presence of capital mobility and cross-border pollution. *Southern Economic Journal 84*(1), 317–336.

Weitzman, M. L. (1974). Prices vs. quantities. *The Review of Economic Studies 41*(4), 477–491.

Withagen, C. (1994). Pollution and exhaustibility of fossil fuels. *Resource and Energy Economics 16*(3), 235 – 242.

A Carbon Taxation

Comparative Statics

In order to derive the comparative static effects of marginal changes in local carbon taxes τ_{i1} or τ_{i2}, the market equilibrium conditions, as stated above, in the text are differentiated totally and subsequently the symmetry assumption is applied. Beginning (10) - (12) we obtain

$$\sum_{k=1}^{n} \mathrm{d}c_{kt} = F_t' \sum_{k=1}^{n} \mathrm{d}e_{kt}, \tag{69}$$

$$\sum_{k=1}^{n} \mathrm{d}b_k = 0, \tag{70}$$

$$\sum_{k=1}^{n} \mathrm{d}e_{kt} = \mathrm{d}e_t^s. \tag{71}$$

Differentiation of (2) for $t = 1, 2$, (4) and (5) yields

$$p_1 \, \mathrm{d}r + [1 + r] \, \mathrm{d}p_1 = \mathrm{d}p_2, \tag{72}$$

$$\mathrm{d}e_1^s = - \, \mathrm{d}e_2^s, \tag{73}$$

$$F_1'' \, \mathrm{d}e_{i1} = \mathrm{d}p_1 + \mathrm{d}\tau_{i1}, \tag{74}$$

$$F_2'' \, \mathrm{d}e_{i2} = \mathrm{d}p_2 + \mathrm{d}\tau_{i2}, \tag{75}$$

where $\mathrm{d}\tau_{i1} \neq 0, \mathrm{d}\tau_{i2} = 0$ when solving for comparative static effects of τ_{i1} (or $\mathrm{d}\tau_{i1} = 0, \mathrm{d}\tau_{i2} \neq 0$ for comparative static effects of τ_{i2}) and $\mathrm{d}\tau_{j1} = \mathrm{d}\tau_{j2} = 0$ for $j \neq i$.

Next, we turn to (7) and (8) where we use (1), (3) and $T_{it} = \tau_{it} e_{it}$ for $t = 1, 2$. Subsequently, we totally differentiate and simplify by using (2), which gives

$$\mathrm{d}c_{i1} = [F_1' - p_1 - \tau_1]\,\mathrm{d}e_{i1} - [\mathrm{d}p_1 + \mathrm{d}\tau_{i1}]e_1 + \frac{e_1^s\,\mathrm{d}p_1 + p_1\,\mathrm{d}e_1^s}{n} + e_1\,\mathrm{d}\tau_{i1} + \tau_1\,\mathrm{d}e_1 + \mathrm{d}b_i,$$

$$\mathrm{d}c_{i1} = \tau_1\,\mathrm{d}e_{i1} + \frac{p_1}{n}\,\mathrm{d}e_1^s + \mathrm{d}b_i, \tag{76}$$

$$\mathrm{d}c_{i2} = [F_2' - p_2 - \tau_2]\,\mathrm{d}e_{i2} - [\mathrm{d}p_2 + \mathrm{d}\tau_{i2}]e_2 + \frac{e_2^s\,\mathrm{d}p_2 + p_2\,\mathrm{d}e_2^s}{n}$$
$$+ e_2\,\mathrm{d}\tau_{i2} + \tau_2\,\mathrm{d}e_{i2} - b\,\mathrm{d}r - [1+r]\,\mathrm{d}b_i,$$

$$\mathrm{d}c_{i2} = \tau_2\,\mathrm{d}e_{i2} + \frac{p_2}{n}\,\mathrm{d}e_2^s - [1+r]\,\mathrm{d}b_i, \tag{77}$$

Totally differentiating the household's the first-order condition (9) yields

$$\mathrm{d}r = \mathfrak{U}_1\,\mathrm{d}c_{i1} + \mathfrak{U}_2\,\mathrm{d}c_{i2} \tag{78}$$

$$\text{with}\quad \mathfrak{U}_s = \frac{\partial\left[\frac{U_1}{U_2}\right]}{\partial c_s} = \frac{U_{1s}U_2 - U_{s2}U_1}{[U_2]^2}; \quad s = 1, 2,$$

where $\mathfrak{U}_1 < 0$; $\mathfrak{U}_2 > 0$, which follows from the assumption that c_{i1} and c_{i2} are normal goods. Equations (70) -(78) give the system of differentiated equilibrium conditions.

We proceed by summing up (74), (75) and (78) over all countries and use (69), (71) and (73) to obtain

$$n\,\mathrm{d}p_1 = -\,\mathrm{d}\tau_{i1} + \sum_{k=1}^{n} F_1''\,\mathrm{d}e_{k1} = -\,\mathrm{d}\tau_{i1} + F_1''\,\mathrm{d}e_1^s, \tag{79}$$

$$n\,\mathrm{d}p_2 = -\,\mathrm{d}\tau_{i2} + \sum_{k=1}^{n} F_2''\,\mathrm{d}e_{k2} = -\,\mathrm{d}\tau_{i2} - F_2''\,\mathrm{d}e_1^s, \tag{80}$$

$$n\,\mathrm{d}r = \sum_{k=1}^{n} [\mathfrak{U}_1\,\mathrm{d}c_{k1} + \mathfrak{U}_2\,\mathrm{d}c_{k2}] = \mathfrak{F}\,\mathrm{d}e_1^s, \tag{81}$$

where $\mathfrak{F} = \mathfrak{U}_1 F_1' - \mathfrak{U}_2 F_2'$. Then, we plug these into (72) and solve for $\mathrm{d}e_1^s$ to receive

$$np_1\mathfrak{F}\,\mathrm{d}e_1^s + [1+r]\,n\left[-\,\mathrm{d}\tau_{i1} + F_1''\,\mathrm{d}e_1^s\right] = n[-\,\mathrm{d}\tau_{i2} - F_2''\,\mathrm{d}e_1^s]$$
$$\Leftrightarrow \mathrm{d}e_1^s = \frac{[1+r]\,\mathrm{d}\tau_{i1}}{\mathfrak{G}} - \frac{\mathrm{d}\tau_{i2}}{\mathfrak{G}}, \tag{82}$$

where $\mathfrak{G} = \mathfrak{F}p_1 + F_1''[1+r] + F_2''$, which we insert back into (79), (80) and (81) to obtain

$$\Rightarrow \mathrm{d}p_1 = \frac{-\left[\mathfrak{F}p_1 + F_1''[1+r] + F_2''\right]\mathrm{d}\tau_{i1} + [1+r]\,F_1''\,\mathrm{d}\tau_{i1} - F_1''\,\mathrm{d}\tau_{i2}}{n\mathfrak{G}}$$
$$= -\frac{[\mathfrak{F}p_1 + F_2'']\,\mathrm{d}\tau_{i1}}{n\mathfrak{G}} - \frac{F_1''\,\mathrm{d}\tau_{i2}}{n\mathfrak{G}}, \tag{83}$$

$$\Rightarrow \mathrm{d}p_2 = \frac{-\left[\mathfrak{F}p_1 + F_1''[1+r] + F_2''\right]\mathrm{d}\tau_{i2} - [1+r]\,F_2''\,\mathrm{d}\tau_{i1} + F_2''\,\mathrm{d}\tau_{i2}}{n\mathfrak{G}}$$
$$= -\frac{[1+r]\,F_2''\,\mathrm{d}\tau_{i1}}{n\mathfrak{G}} - \frac{\left[\mathfrak{F}p_1 + [1+r]\,F_1''\right]\mathrm{d}\tau_{i2}}{n\mathfrak{G}}, \tag{84}$$

$$\Rightarrow \mathrm{d}r = \frac{[1+r]\,\mathfrak{F}\,\mathrm{d}\tau_{i1}}{n\mathfrak{G}} - \frac{\mathfrak{F}\,\mathrm{d}\tau_{i2}}{n\mathfrak{G}}. \tag{85}$$

Then we consider countries i and $j \neq i$ and insert (83) into (74) and (84) into (75) to get

$$\begin{aligned}
\Rightarrow \mathrm{d}e_{i1} &= \frac{\mathrm{d}p_1 + \mathrm{d}\tau_{i1}}{F_1''} = \frac{\mathrm{d}\tau_{i1} - \frac{\left[\mathfrak{F}p_1 + F_2''\right]\mathrm{d}\tau_{i1}}{n\mathfrak{G}} - \frac{F_1''\,\mathrm{d}\tau_{i2}}{n\mathfrak{G}}}{F_1''} \\
&= \frac{\left[n\mathfrak{G} - \left[\mathfrak{F}p_1 + F_2''\right]\right]\mathrm{d}\tau_{i1}}{nF_1''\mathfrak{G}} - \frac{\mathrm{d}\tau_{i2}}{n\mathfrak{G}}, \qquad (86) \\
\Rightarrow \mathrm{d}e_{j1} &= \frac{\mathrm{d}p_1}{F_1''} = \frac{-\frac{\left[\mathfrak{F}p_1 + F_2''\right]\mathrm{d}\tau_{i1}}{n\mathfrak{G}} - \frac{F_1''\,\mathrm{d}\tau_{i2}}{n\mathfrak{G}}}{F_1''} \\
&= -\frac{\left[\mathfrak{F}p_1 + F_2''\right]\mathrm{d}\tau_{i1}}{nF_1''\mathfrak{G}} - \frac{\mathrm{d}\tau_{i2}}{n\mathfrak{G}}, \qquad (87)
\end{aligned}$$

$$\begin{aligned}
\Rightarrow \mathrm{d}e_{i2} &= \frac{\mathrm{d}p_2 + \mathrm{d}\tau_{i2}}{F_2''} = \frac{\mathrm{d}\tau_{i2} - \frac{[1+r]F_2''\,\mathrm{d}\tau_{i1}}{n\mathfrak{G}} - \frac{\left[\mathfrak{F}p_1 + [1+r]F_1''\right]\mathrm{d}\tau_{i2}}{n\mathfrak{G}}}{F_2''} \\
&= -\frac{[1+r]\,\mathrm{d}\tau_{i1}}{n\mathfrak{G}} + \frac{\left[n\mathfrak{G} - \left[\mathfrak{F}p_1 + [1+r]\,F_1''\right]\right]\mathrm{d}\tau_{i2}}{nF_2''\mathfrak{G}}, \qquad (88) \\
\Rightarrow \mathrm{d}e_{j2} &= \frac{\mathrm{d}p_2}{F_2''} = \frac{-\frac{[1+r]F_2''\,\mathrm{d}\tau_{i1}}{n\mathfrak{G}} - \frac{\left[\mathfrak{F}p_1 + [1+r]F_1''\right]\mathrm{d}\tau_{i2}}{n\mathfrak{G}}}{F_2''} \\
&= -\frac{[1+r]\,\mathrm{d}\tau_{i1}}{n\mathfrak{G}} - \frac{\left[\mathfrak{F}p_1 + [1+r]\,F_1''\right]\mathrm{d}\tau_{i2}}{nF_2''\mathfrak{G}}. \qquad (89)
\end{aligned}$$

Finally, we take (83) - (89) to compute the comparative static effects of changing τ_{i1} (τ_{i2}) setting $\mathrm{d}\tau_{i2} = 0$ ($\mathrm{d}\tau_{i1} = 0$). Thereby, we get

$$\frac{\partial r}{\partial \tau_{i1}} = \frac{[1+r]\mathfrak{F}}{n\mathfrak{G}} > 0, \qquad \frac{\partial r}{\partial \tau_{i2}} = \frac{-\mathfrak{F}}{n\mathfrak{G}} < 0, \qquad (90)$$

$$\frac{\partial p_1}{\partial \tau_{i1}} = \frac{-F_2'' - \mathfrak{F}p_1}{n\mathfrak{G}} < 0, \qquad \frac{\partial p_1}{\partial \tau_{i2}} = \frac{-F_1''}{n\mathfrak{G}} < 0, \qquad (91)$$

$$\frac{\partial p_2}{\partial \tau_{i1}} = \frac{-[1+r]F_2''}{n\mathfrak{G}} < 0, \qquad \frac{\partial p_2}{\partial \tau_{i2}} = \frac{-[1+r]F_1'' - p_1\mathfrak{F}}{n\mathfrak{G}} < 0, \qquad (92)$$

$$\frac{\partial e_{i1}}{\partial \tau_{i1}} = \frac{n\mathfrak{G} - [F_2'' + \mathfrak{F}p_1]}{nF_1''\mathfrak{G}} < 0, \qquad \frac{\partial e_{i1}}{\partial \tau_{i2}} = -\frac{1}{n\mathfrak{G}} > 0, \qquad (93)$$

$$\frac{\partial e_{i2}}{\partial \tau_{i1}} = -\frac{1+r}{n\mathfrak{G}} > 0, \qquad \frac{\partial e_{i2}}{\partial \tau_{i2}} = \frac{n\mathfrak{G} - \left[[1+r]F_1'' + \mathfrak{F}p_1\right]}{nF_2''\mathfrak{G}} < 0, \qquad (94)$$

$$\frac{\partial e_1^s}{\partial \tau_{i1}} = \frac{1+r}{\mathfrak{G}} < 0, \qquad \frac{\partial e_1^s}{\partial \tau_{i2}} = -\frac{1}{\mathfrak{G}} > 0, \qquad (95)$$

$$\frac{\partial e_{j1}}{\partial \tau_{i1}} = \frac{-F_2'' - \mathfrak{F}p_1}{nF_1''\mathfrak{G}} > 0, \qquad \frac{\partial e_{j1}}{\partial \tau_{i2}} = -\frac{1}{n\mathfrak{G}} > 0, \qquad (96)$$

$$\frac{\partial e_{j2}}{\partial \tau_{i1}} = -\frac{1+r}{n\mathfrak{G}} > 0, \qquad \frac{\partial e_{j2}}{\partial \tau_{i2}} = \frac{-[1+r]F_1'' - \mathfrak{F}p_1}{nF_2''\mathfrak{G}} > 0, \qquad (97)$$

where $\mathfrak{F} = \mathfrak{U}_1 F_1' - \mathfrak{U}_2 F_2' < 0$ and $\mathfrak{G} = \mathfrak{F}p_1 + F_1''[1+r] + F_2'' < 0$.

Proof of Proposition 1

Take the solution to problem (16) stated in Proposition 1, here slightly adapted

$$\tau_1^* = \frac{D'}{U_1} \cdot \frac{\mathfrak{N}_1}{\mathfrak{D}}, \ \tau_2^* = \frac{D'}{U_2} \cdot \frac{\mathfrak{N}_2}{\mathfrak{D}},$$

$$\text{with} \quad \mathfrak{N}_1 := \frac{\partial e_1^s}{\partial \tau_{i1}} \frac{\partial e_{i2}}{\partial \tau_{i2}} - \frac{\partial e_1^s}{\partial \tau_{i2}} \frac{\partial e_{i2}}{\partial \tau_{i1}}, \ \mathfrak{N}_2 := \frac{\partial e_1^s}{\partial \tau_{i2}} \frac{\partial e_{i1}}{\partial \tau_{i1}} - \frac{\partial e_1^s}{\partial \tau_{i1}} \frac{\partial e_{i1}}{\partial \tau_{i2}} \quad \mathfrak{D} := \frac{\partial e_{i1}}{\partial \tau_{i1}} \frac{\partial e_{i2}}{\partial \tau_{i2}} - \frac{\partial e_{i2}}{\partial \tau_{i1}} \frac{\partial e_{i1}}{\partial \tau_{i2}}.$$

Due to the assumptions regarding $U(\cdot)$ and $D(\cdot)$ we have $\frac{D'}{U_t} > 0$ for $t = 1, 2$. Turning to the the terms $\frac{\mathfrak{N}_1}{\mathfrak{D}}$ and $\frac{\mathfrak{N}_1}{\mathfrak{D}}$, we obtain for denominator

$$\mathfrak{D} = \frac{\partial e_{i1}}{\partial \tau_{i1}} \frac{\partial e_{i2}}{\partial \tau_{i2}} - \frac{\partial e_{i2}}{\partial \tau_{i1}} \frac{\partial e_{i1}}{\partial \tau_{i2}} = \frac{n\mathfrak{G} - [F_2'' + \mathfrak{F}p_1]}{nF_1''\mathfrak{G}} \cdot \frac{n\mathfrak{G} - \big[[1+r]F_1'' + \mathfrak{F}p_1\big]}{nF_2''\mathfrak{G}} - \frac{-[1+r]}{n\mathfrak{G}} \cdot \frac{-1}{n\mathfrak{G}}$$

$$\mathfrak{D} = \frac{[n-1][n\mathfrak{G} - \mathfrak{F}p_1]}{n^2 F_1'' F_2'' \mathfrak{G}} > 0, \tag{98}$$

where $n\mathfrak{G} - \mathfrak{F}p_1 = [n-1]\mathfrak{F}p_1 + n[F_1''[1+r] + F_2''] < 0$ with $\mathfrak{F} < 0$ (see above in this Appendix). The sign of numerator $\mathfrak{N}_1$ is

$$\mathfrak{N}_1 = \frac{[1+r]}{\mathfrak{G}} \cdot \frac{n\mathfrak{G} - [F_1''[1+r] + \mathfrak{F}p_1]}{nF_2''\mathfrak{G}} - \frac{1+r}{n\mathfrak{G}} \cdot \frac{1}{\mathfrak{G}},$$

$$\mathfrak{N}_1 = \frac{[n-1][1+r]}{nF_2''\mathfrak{G}} > 0, \tag{99}$$

where $\mathfrak{G} < 0$ (see above in this Appendix), and that of $\mathfrak{N}_2$ is

$$\mathfrak{N}_2 = \frac{-1}{\mathfrak{G}} \cdot \frac{n\mathfrak{G} - 1[F_2'' + \mathfrak{F}p_1]}{nF_1''\mathfrak{G}} - \frac{1+r}{\mathfrak{G}} \cdot \frac{-1}{n\mathfrak{G}},$$

$$\mathfrak{N}_2 = \frac{1-n}{nF_1''\mathfrak{G}} < 0. \tag{100}$$

Given (98), (99) and (100) it follows that

$$\tau_1^* > 0, \tag{101}$$

$$\tau_2^* < 0, \tag{102}$$

as well as that

$$0 < \frac{\mathfrak{N}_1}{\mathfrak{D}} = \frac{nF_1''[1+r]}{n\mathfrak{G} - \mathfrak{F}p_1} < 1, \tag{103}$$

$$0 < -\frac{\mathfrak{N}_2}{\mathfrak{D}} = \frac{nF_2''}{n\mathfrak{G} - \mathfrak{F}p_1} < 1, \tag{104}$$

recalling that $\mathfrak{G} = \mathfrak{F}p_1 + F_1''[1+r] + F_2''$. This proves Proposition 1.

B Cap Policy Equilibrium with Local Permit Markets

Incentive for country i to introduce a cap in period 2 In order to derive (30) and (31) we take (21) and (22) and plug in π_{it} and π_t^R from (3), (19) and apply $e_{i1} = \hat{e}_{i1}$.

We then differentiate with respect to $\hat{e}_{i2}$ and simplify by (20) for $t = 1$, (24), (28) and (29) as well as by the symmetry assumption, i. e. symmetric policy choice in period 1 ($\hat{e}_{i1} = \hat{e}_{j1} = \frac{e_1^s}{n}$), a symmetric market equilibrium, i.e. $e_{i2} = e_{j2} = \frac{e_2^s}{n}, b_i = b_j = 0$ and a marginally binding cap in country i ($\hat{e}_{i2} = e_{i2}$), which gives

$$\begin{aligned}\frac{\partial c_{i1}}{\partial \hat{e}_{i2}} &= \left[F_1' - p_1 - \phi_{i1}\right] \underbrace{\frac{\partial \hat{e}_{i1}}{\partial \hat{e}_{i2}}}_{=0} - \left[\frac{\partial p_1}{\partial \hat{e}_{i2}} + \frac{\partial \phi_{i1}}{\partial \hat{e}_{i2}}\right] \hat{e}_{i1} + \hat{e}_{i1} \frac{\partial \phi_{i1}}{\partial \hat{e}_{i2}} + \frac{1}{n}\left[p_1 \underbrace{\frac{\partial e_1^s}{\partial \hat{e}_{i2}}}_{=0} + e_1^s \frac{\partial p_1}{\partial \hat{e}_{i2}}\right] + \frac{\partial b_i}{\partial \hat{e}_{i2}} \\ &= \frac{\partial b_i}{\partial \hat{e}_{i2}},\end{aligned} \tag{105}$$

$$\begin{aligned}\frac{\partial c_{i2}}{\partial \hat{e}_{i2}} &= F_2' - p_2 - \phi_{i2} - \left[\frac{\partial p_2}{\partial \hat{e}_{i2}} + \frac{\partial \phi_{i2}}{\partial \hat{e}_{i2}}\right] \hat{e}_{i2} + \phi_{i2} + \hat{e}_{i2} \frac{\partial \phi_{i2}}{\partial \hat{e}_{i2}} + \frac{1}{n}\left[p_2 \underbrace{\frac{\partial e_2^s}{\partial \hat{e}_{i2}}}_{=0} + e_1^s \frac{\partial p_2}{\partial \hat{e}_{i2}}\right] \\ &\quad - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i2}} - \underbrace{b_i}_{=0} \frac{\partial r}{\partial \hat{e}_{i2}} \\ &= \phi_{i2} - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i2}}.\end{aligned} \tag{106}$$

To derive (32) we differentiate (23) and simplify by use of (9), (28), (30), (31) with $\phi_{i2} = 0$ and obtain

$$\begin{aligned}\frac{\partial W_i}{\partial \hat{e}_{i2}} &= U_1 \frac{\partial c_{i1}}{\partial \hat{e}_{i2}} + U_2 \frac{\partial c_{i2}}{\partial \hat{e}_{i2}} - D' \frac{\partial e_1^s}{\partial \hat{e}_{i2}} \\ &= U_1 \left[\frac{\partial b_i}{\partial \hat{e}_{i2}}\right] + U_2 \left[\underbrace{\phi_{i2}}_{=0} - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i2}}\right] = 0.\end{aligned} \tag{107}$$

Incentive for country i to introduce a cap in period 1 We differentiate (21) and (22) with respect to $\hat{e}_{i1}$, with $e_{i1} = \hat{e}_{i1}$ and $\phi_{i2} = 0$. After differentiating we apply $\phi_{i1} = 0$ since symmetric caps set in period 1 are marginally binding. To simplify we use (35) and (36) and apply the symmetry assumption, i. e. a symmetric policy choice in period 1 ($\hat{e}_{i1} = \hat{e}_{j1} = \frac{e_1^s}{n}$), a symmetric market equilibrium, i. e. $e_{i2} = e_{j2} = \frac{e_2^s}{n}, b_i = b_j = 0$).

$$\begin{aligned}\frac{\partial c_{i1}}{\partial \hat{e}_{i1}} &= F_1' - p_1 - \phi_{i1} - \left[\frac{\partial p_1}{\partial \hat{e}_{i1}} + \frac{\partial \phi_{i1}}{\partial \hat{e}_{i1}}\right] \hat{e}_{i1} + \phi_{i1} + \frac{\partial \phi_{i1}}{\partial \hat{e}_{i1}} \hat{e}_{i1} + \frac{1}{n}\left[p_1 \underbrace{\frac{\partial e_1^s}{\partial \hat{e}_{i1}}}_{=1} + e_1^s \frac{\partial p_1}{\partial \hat{e}_{i1}}\right] + \frac{\partial b_i}{\partial \hat{e}_{i1}}, \\ \frac{\partial c_{i1}}{\partial \hat{e}_{i1}} &= \phi_{i1} + \frac{p_1}{n} + \frac{\partial b_i}{\partial \hat{e}_{i1}},\end{aligned} \tag{108}$$

$$\frac{\partial c_{i2}}{\partial \hat{e}_{i1}} = \left[F_2' - p_2\right] \cdot \frac{\partial e_{i2}}{\partial \hat{e}_{i1}} - e_{i2}\frac{\partial p_2}{\partial \hat{e}_{i1}} + \frac{1}{n}\left[p_2 \underbrace{\frac{\partial e_2^s}{\partial \hat{e}_{i1}}}_{=-1} + e_2^s \frac{\partial p_2}{\partial \hat{e}_{i2}}\right] - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i1}} - b_i \frac{\partial r}{\partial \hat{e}_{i1}},$$

$$\frac{\partial c_{i2}}{\partial \hat{e}_{i1}} = -\frac{p_2}{n} - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i1}}. \tag{109}$$

To derive (39), we differentiate (23) with respect to $\hat{e}_{i1}$ and plug in (35), (37) and (38). Then we use (5) and (9) to simplify and obtain

$$\begin{aligned}
\frac{\partial W_i}{\partial \hat{e}_{i1}} &= U_1 \frac{\partial c_{i1}}{\partial \hat{e}_{i1}} + U_2 \frac{\partial c_{i2}}{\partial \hat{e}_{i1}} - D' \underbrace{\frac{\partial e_1^s}{\partial \hat{e}_{i1}}}_{=1} \\
&= U_1 \left[\frac{p_1}{n} + \frac{\partial b_i}{\partial \hat{e}_{i1}}\right] + U_2 \left[-\frac{p_2}{n} - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i1}}\right] - D' \\
&= U_2 \left[\frac{[1+r]p_1}{n} + [1+r]\frac{\partial b_i}{\partial \hat{e}_{i2}} - \frac{p_2}{n} - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i2}}\right] - D' = -D' < 0.
\end{aligned} \tag{110}$$

Optimal decentral choice of caps in period 1 Assuming a symmetric policy choice $\hat{e}_{i1} = \hat{e}_1$, we have $\phi_{i1} = \phi_{j1} = \phi_1 \geq 0$ due to (20) and a firm choice satisfying $e_{i1} = \hat{e}_1$. Then, deriving the first-order condition of (40) and subsequently using (35), (108) and (109) and simplifying with the help of (5) and (9) yields

$$\begin{aligned}
\frac{\partial W_i}{\partial \hat{e}_{i1}} &= U_1 \frac{\partial c_{i1}}{\partial \hat{e}_{i1}} + U_2 \frac{\partial c_{i2}}{\partial \hat{e}_{i1}} - D' \frac{\partial e_1^s}{\partial \hat{e}_{i1}} = 0 \\
&= U_1 \left[\phi_1 + \frac{p_1}{n} + \frac{\partial b_i}{\partial \hat{e}_{i1}}\right] + U_2 \left[-\frac{p_2}{n} - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i1}}\right] - D' = 0 \\
&= U_1\phi_1 + U_2 \left[[1+r]\frac{p_1}{n} + [1+r]\frac{\partial b_i}{\partial \hat{e}_{i1}} - \frac{p_2}{n} - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i1}}\right] - D' = 0 \\
&= U_1\phi_1 - D' = 0.
\end{aligned} \tag{111}$$

C Cap Policy with Linked Permit Markets

Tightening $\check{e}_{i2}$ beyond the marginally binding level Suppose that all countries i, j impose symmetric, marginally binding caps $\check{e}_{it} = \check{e}_{ij} = \check{e}_t$ in periods 1 and 2, i. e. $\check{e}_{it} = e_{kt}^{LF}$, where e_{kt}^{LF} denotes resource demand in country i and period t in the absence of policy. The market equilibrium is described by (4), (5), (9), (11), (12), (45) and (46), which serves as the point of departure for determining the comparative static effects of $\check{e}_{i2}$ ($\mathrm{d}\check{e}_{i2} \neq 0$ and $\mathrm{d}\check{e}_{i1} = \mathrm{d}\check{e}_{j1} = \mathrm{d}\check{e}_{j2} = 0$). First, we use (11) in (46) for period 1 to substitute for $\sum_{k=1}^{n} e_{k1}$. Then we differentiate and obtain

$$\frac{\partial e_1^s}{\partial \check{e}_{i2}} = 0, \tag{112}$$

which we use after differentiating (4) with respect to $\check{e}_{i2}$ to receive

$$\frac{\partial e_2^s}{\partial \check{e}_{i2}} = 0. \tag{113}$$

Then we differentiate (7) and (8), where π_{it} is given by (44), $T_{it} = \frac{\alpha}{n}\varphi_t \sum_{k=1}^{n} \check{e}_{kt}$, and π_1^R and π_2^R are given by (3) and simplify by use of (45), (112) and (113) as well as the symmetry assumption, i. e. $\check{e}_{it} = \check{e}_{jt} = e_{i2} = e_{j2} = \frac{e_t^s}{n}$, $b_i = b_j = 0$, $F(e_{it})' = F_t'$ which is due to (45) as well as the symmetric policy choice, which gives

$$\begin{aligned}\frac{\partial c_{i1}}{\partial \check{e}_{i2}} &= \underbrace{\left[F_1' - p_1 - \varphi_1\right]}_{=0} \frac{\partial e_{i1}}{\partial \check{e}_{i2}} - \left[\frac{\partial p_1}{\partial \check{e}_{i2}} + \frac{\partial \varphi_1}{\partial \check{e}_{i2}}\right] e_{i1} + \underbrace{[1-\alpha]\check{e}_{i1}\frac{\partial \varphi_1}{\partial \check{e}_{i2}} + \frac{\alpha}{n}\frac{\partial \varphi_1}{\partial \check{e}_{i2}} \sum_{k=1}^{n} \check{e}_{k1}}_{=\frac{\partial \varphi_1}{\partial \check{e}_{i2}}\check{e}_{i1}} \\ &\quad + \frac{1}{n}\left[p_1 \underbrace{\frac{\partial e_1^s}{\partial \check{e}_{i2}}}_{=0} + e_1^s \frac{\partial p_1}{\partial \check{e}_{i2}}\right] + \frac{\partial b_i}{\partial \check{e}_{i2}} \\ \frac{\partial c_{i1}}{\partial \check{e}_{i2}} &= \frac{\partial b_i}{\partial \check{e}_{i2}},\end{aligned} \tag{114}$$

$$\begin{aligned}\frac{\partial c_{i2}}{\partial \check{e}_{i2}} &= \underbrace{\left[F_2' - p_2 - \varphi_2\right]}_{=0} \frac{\partial e_{i2}}{\partial \check{e}_{i2}} - \left[\frac{\partial p_2}{\partial \check{e}_{i2}} + \frac{\partial \varphi_2}{\partial \check{e}_{i2}}\right] e_{i2} + \underbrace{[1-\alpha]\check{e}_{i1}\frac{\partial \varphi_2}{\partial \check{e}_{i2}} + \frac{\alpha}{n}\frac{\partial \varphi_2}{\partial \check{e}_{i2}} \sum_{k=1}^{n} \check{e}_{k2}}_{=\frac{\partial \varphi_2}{\partial \check{e}_{i2}}\check{e}_{i2}} \\ &\quad + [1-\alpha]\varphi_2 + \frac{\alpha}{n}\varphi_2 + \frac{1}{n}\left[p_2 \underbrace{\frac{\partial e_2^s}{\partial \check{e}_{i2}}}_{=0} + e_1^s \frac{\partial p_2}{\partial \check{e}_{i2}}\right] - [1+r]\frac{\partial b_i}{\partial \check{e}_{i2}} - \underbrace{b_i}_{=0} \frac{\partial r}{\partial \check{e}_{i2}} \\ \frac{\partial c_{i2}}{\partial \check{e}_{i2}} &= \left[1 - \alpha + \frac{\alpha}{n}\right]\varphi_2 - [1+r]\frac{\partial b_i}{\partial \check{e}_{i2}}.\end{aligned} \tag{115}$$

As in Section 3, we formulate welfare as a function of the caps in both periods

$$W_i = U\left(c_{i1}\left(\check{e}_{i1}, \check{e}_{i2}\right), c_{i2}\left(\check{e}_{i1}, \check{e}_{i2}\right)\right) - D\left(e_1^s\left(\check{e}_{i1}, \check{e}_{i2}\right)\right). \tag{116}$$

Differentiating (116) with respect to $\check{e}_{i2}$ we use (112), (114), (115) with $\varphi_1 = \varphi_2 = 0$, since we assume that the point of departure exhibits marginally binding caps in periods 1 and 2, and simplify with the help of (9) to obtain

$$\begin{aligned}\frac{\partial W_i}{\partial \check{e}_{i2}} &= U_1 \frac{\partial c_{i1}}{\partial \check{e}_{i2}} + U_2 \frac{\partial c_{i2}}{\partial \check{e}_{i2}} - D' \frac{\partial e_1^s}{\partial \check{e}_{i2}} \\ &= U_1 \left[\frac{\partial b_i}{\partial \check{e}_{i2}}\right] + U_2 \left[-[1+r]\frac{\partial b_i}{\partial \check{e}_{i2}}\right] \\ &= U_2 \left[[1+r]\frac{\partial b_i}{\partial \check{e}_{i2}} - [1+r]\frac{\partial b_i}{\partial \check{e}_{i2}}\right] = 0.\end{aligned} \tag{117}$$

Equation (117) states that the net effect of tightening the cap in country i in period 2 departing from a policy choice of marginally binding caps in both peridos has no effect on domestic welfare.

Tightening $\check{e}_{i1}$ beyond the marginally binding level Based on the finding above, i. e. there is no incentive to tighten the second period cap $\check{e}_{i2}$ beyond the marginally binding level, suppose that all countries i, j impose symmetric, marginally binding caps $\check{e}_{it} = \check{e}_{ij} = \check{e}_t$ only in period 1. The market equilibrium is described by (4), (5), (9), (11), (12), and for $t = 1$ (45) and (46), while for $t = 2$ we adapt (45) to obtain

$$F'(e_{k2}) = p_2. \tag{118}$$

This market equilibrium serves as the point of departure for determining the comparative static effects of $\check{e}_{i1}$ ($\mathrm{d}\check{e}_{i1} \neq 0$ and $\mathrm{d}\check{e}_{j1} = 0$). First, we use (11) in (46) for period 1 to substitute for $\sum_{k=1}^{n} e_{k1}$. Then we differentiate and obtain

$$\frac{\partial e_1^s}{\partial \check{e}_{i1}} = 1, \tag{119}$$

which we use after differentiating (4) with respect to $\check{e}_{i1}$ to receive

$$\frac{\partial e_2^s}{\partial \check{e}_{i1}} = -1. \tag{120}$$

Then we differentiate (7) and (8), where π_{i1} is given by (44) and for π_{i2} we take (44) with $\varphi_2 = 0$, $T_{i1} = \frac{\alpha}{n}\varphi_1 \sum_{k=1}^{n} \check{e}_{k1}$ and $T_{i2} = 0$, and π_1^R and π_2^R are given by (3). To simplify, we make use of (45) for $t = 1$, (118), (119) and (120) as well as the symmetry assumption, as outlined above in this Appendix, which gives for period 1

$$\begin{aligned}
\frac{\partial c_{i1}}{\partial \check{e}_{i1}} &= \underbrace{\left[F_1' - p_1 - \varphi_1\right]}_{=0} \frac{\partial e_{i1}}{\partial \check{e}_{i1}} - \left[\frac{\partial p_1}{\partial \check{e}_{i1}} + \frac{\partial \varphi_1}{\partial \check{e}_{i1}}\right] e_{i1} + \underbrace{[1-\alpha]\check{e}_{i1}\frac{\partial \varphi_1}{\partial \check{e}_{i1}} + \frac{\alpha}{n}\frac{\partial \varphi_1}{\partial \check{e}_{i1}}\sum_{k=1}^{n}\check{e}_{k1}}_{=\frac{\partial \varphi_1}{\partial \check{e}_{i1}}\check{e}_{i1}} \\
&\quad + [1-\alpha]\varphi_1 + \frac{\alpha}{n}\varphi_1 + \frac{1}{n}\left[p_1 \underbrace{\frac{\partial e_1^s}{\partial \check{e}_{i1}}}_{=1} + e_1^s \frac{\partial p_1}{\partial \check{e}_{i1}}\right] + \frac{\partial b_i}{\partial \check{e}_{i1}} \\
\frac{\partial c_{i1}}{\partial \check{e}_{i1}} &= \left[1 - \alpha + \frac{\alpha}{n}\right]\varphi_1 + \frac{p_1}{n} + \frac{\partial b_i}{\partial \check{e}_{i1}},
\end{aligned} \tag{121}$$

and for period 2

$$\begin{aligned}
\frac{\partial c_{i2}}{\partial \check{e}_{i1}} &= \underbrace{\left[F_2' - p_2\right]}_{=0} \frac{\partial e_{i2}}{\partial \check{e}_{i1}} - \frac{\partial p_2}{\partial \check{e}_{i1}} e_{i2} + \frac{1}{n}\left[p_2 \underbrace{\frac{\partial e_2^s}{\partial \check{e}_{i1}}}_{=-1} + e_1^s \frac{\partial p_2}{\partial \check{e}_{i1}}\right] - [1+r]\frac{\partial b_i}{\partial \check{e}_{i1}} - \underbrace{b_i}_{=0}\frac{\partial r}{\partial \check{e}_{i1}} \\
\frac{\partial c_{i2}}{\partial \check{e}_{i1}} &= -\frac{p_2}{n} - [1+r]\frac{\partial b_i}{\partial \check{e}_{i1}}.
\end{aligned} \tag{122}$$

Since countries are assumed to conduct cap-and-trade policy only in period 1, we adapt (116) from above accordingly, which then reads

$$W_i = U\left(c_{i1}\left(\check{e}_{i1}\right), c_{i2}\left(\check{e}_{i1}\right)\right) - D\left(e_1^s\left(\check{e}_{i1}\right)\right). \tag{123}$$

Then differentiating (123) with respect to $\check{e}_{i1}$, plugging in (121) with $\varphi_1 = 0$ (just marginally binding caps), (122) as well as (119) and simplifying by use of (5) and (9) gives

$$\begin{aligned}
\frac{\partial W_i}{\partial \check{e}_{i1}} &= U_1 \frac{\partial c_{i1}}{\partial \check{e}_{i1}} + U_2 \frac{\partial c_{i2}}{\partial \check{e}_{i1}} - D' \frac{\partial e_1^s}{\partial \check{e}_{i1}} \\
&= U_1 \left[\frac{p_1}{n} + \frac{\partial b_i}{\partial \check{e}_{i1}}\right] + U_2 \left[-\frac{p_2}{n} - [1+r] \frac{\partial b_i}{\partial \check{e}_{i1}}\right] - D' \\
&= U_2 \left[[1+r]\frac{p_1}{n} + [1+r]\frac{\partial b_i}{\partial \check{e}_{i1}} - \frac{p_2}{n} - [1+r]\frac{\partial b_i}{\partial \check{e}_{i1}}\right] - D' = -D' < 0. \qquad (124)
\end{aligned}$$

Equation (124) shows that, when all countries implement cap-and-trade policies with a common permit market, and there is no such policy in period 2, country i has the incentive to tighten its cap unilaterally beyond the marginally binding level.

Policy choice Based on the assessment of the incentive to tighten caps beyond the marginal levels, suppose that all countries implement binding caps in period 1 and that there is no cap-and-trade policy in period 2. Thus, the market equilibrium is given by (4), (5), (9), (11), (12), and for $t = 1$ (45) and (46), while for $t = 2$ (118). Therefore, the comparative static effects given by (119), (121) and (122) from above carry over, which we use in the first-order condition of the policy problem given by (50). Recall, that $\varphi_1 \geq 0$, since we account for the case of strictly binding caps. We use (5) as well as (9) to simplify and obtain

$$\begin{aligned}
\frac{\partial W_i}{\partial \check{e}_{i1}} &= U_1 \frac{\partial c_{i1}}{\partial \check{e}_{i1}} + U_2 \frac{\partial c_{i2}}{\partial \check{e}_{i1}} - D' \frac{\partial e_1^s}{\partial \check{e}_{i1}} = 0 \\
&= U_1 \left[\left[1 - \alpha + \frac{\alpha}{n}\right] \varphi_1 + \frac{p_1}{n} + \frac{\partial b_i}{\partial \check{e}_{i1}}\right] + U_2 \left[-\frac{p_2}{n} - [1+r]\frac{\partial b_i}{\partial \check{e}_{i1}}\right] - D' \\
&= \left[1 - \alpha + \frac{\alpha}{n}\right] U_1 \varphi_1 - D' = 0. \qquad (125)
\end{aligned}$$

D Welfare Analysis

Cooperative Policy

The differentiated budget constraints of the household in country i (7) and (8) are given by (76) and (77) in Appendix A, which we divide by $\mathrm{d}\tau_{i1}$ to obtain

$$\frac{\partial c_{i1}}{\partial \tau_{i1}} = \tau_1 \frac{\partial e_{i1}}{\partial \tau_{i1}} + \frac{\partial e_1^s}{\partial \tau_{i1}} \frac{p_1}{n} + \frac{\partial b_i}{\partial \tau_{i1}}, \qquad (126)$$

$$\frac{\partial c_{i2}}{\partial \tau_{i1}} = \tau_2 \frac{\partial e_{i2}}{\partial \tau_{i1}} + \frac{\partial e_2^s}{\partial \tau_{i1}} \frac{p_2}{n} - [1+r] \frac{\partial b_i}{\partial \tau_{i1}}. \qquad (127)$$

Deriving the differentials of the household budget constraints in country $j \neq i$ follows the same procedure as applied for the derivation of (76) and (77), where $\mathrm{d}\tau_{i1} \neq 0$ and

$\mathrm{d}\tau_{j1} = 0$, and yields the same results. So, dividing (76) and (77) for the case of country j by $\mathrm{d}\tau_{i1} \neq 0$ gives

$$\frac{\partial c_{j1}}{\partial \tau_{i1}} = \tau_1 \frac{\partial e_{j1}}{\partial \tau_{i1}} + \frac{\partial e_1^s}{\partial \tau_{i1}} \frac{p_1}{n} + \frac{\partial b_j}{\partial \tau_{i1}}, \tag{128}$$

$$\frac{\partial c_{j2}}{\partial \tau_{i1}} = \tau_2 \frac{\partial e_{j2}}{\partial \tau_{i1}} + \frac{\partial e_2^s}{\partial \tau_{i1}} \frac{p_2}{n} - [1+r] \frac{\mathrm{d} b_j}{\partial \tau_{i1}}. \tag{129}$$

Next, we use (126) - (129) to compute

$$\frac{\partial c_{i1}}{\partial \tau_{i1}} + [n-1] \frac{\partial c_{j1}}{\partial \tau_{i1}} = \tau_1 \left[\frac{\partial e_{i1}}{\partial \tau_{i1}} + [n-1] \frac{\partial e_{j1}}{\partial \tau_{i1}} \right] + \frac{\partial e_1^s}{\partial \tau_{i1}} p_1 + \underbrace{\frac{\partial b_i}{\partial \tau_{i1}} + [n-1] \frac{\partial b_j}{\partial \tau_{i1}}}_{=0}$$

$$\frac{\partial c_{i1}}{\partial \tau_{i1}} + [n-1] \frac{\partial c_{j1}}{\partial \tau_{i1}} = [\tau_1 + p_1] \frac{\partial e_1^s}{\partial \tau_{i1}}, \tag{130}$$

$$\frac{\partial c_{i2}}{\partial \tau_{i1}} + [n-1] \frac{\partial c_{j2}}{\partial \tau_{i1}} = \tau_2 \left[\frac{\partial e_{i2}}{\partial \tau_{i1}} + [n-1] \frac{\partial e_{j2}}{\partial \tau_{i1}} \right] + \frac{\partial e_2^s}{\partial \tau_{i1}} p_1 - [1+r] \underbrace{\frac{\partial b_i}{\partial \tau_{i1}} + [n-1][1+r] \frac{\partial b_j}{\partial \tau_{i1}}}_{=0}$$

$$\frac{\partial c_{i2}}{\partial \tau_{i1}} + [n-1] \frac{\partial c_{j2}}{\partial \tau_{i1}} = [\tau_2 + p_2] \frac{\partial e_2^s}{\partial \tau_{i1}}, \tag{131}$$

where (12) and (11) were used to simplify. Next, we apply the same procedure to derive the comparative static effects of τ_{i2} on the sum of the budget constraints and obtain

$$\frac{\partial c_{i1}}{\partial \tau_{i2}} + [n-1] \frac{\partial c_{j1}}{\partial \tau_{i2}} = [\tau_1 + p_1] \frac{\partial e_1^s}{\partial \tau_{i1}}, \tag{132}$$

$$\frac{\partial c_{i2}}{\partial \tau_{i2}} + [n-1] \frac{\partial c_{j2}}{\partial \tau_{i2}} = [\tau_2 + p_2] \frac{\partial e_2^s}{\partial \tau_{i2}}. \tag{133}$$

Proof of Lemma 2

Part 1: The relation of carbon fee differentials to emissions We first take the discounted carbon fee differential and use the local production firm's first-order conditions in period 1 and 2 to replace θ_t. Since in the case of taxes a carbon fee applies in each period, we take (2) and replace τ_t by θ_t. Then we use (5) and (9) to simplify and use the notion of symmetry $e_t = \frac{e_t^s}{n}$ in combination with the resource constraint (4) which gives $e_2 = \bar{e}/n - e_1$. Finally we replace c_t in the $U_t(c_1, c_2)$ taking the budget constraint of the household at the symmetric allocation ($b_i = 0$), which gives $c_t = F(e_t) - (p_t + \theta_t)e_t + \theta_t e_t + \frac{p_t e_t^s}{n} = F(e_t)$. The result is

$$\begin{aligned}
\Delta(\theta_1, \theta_2) &= \theta_1 - \frac{\theta_2}{1+r} \\
&= F'(e_1) - p_1 - \frac{F'(e_2) - p_2}{1+r} = F'(e_1) - \frac{F'(e_2)}{1+r} \\
&= F'(e_1) - F'\left(\bar{e}/n - e_1\right) \frac{U_2\Big(F(e_1), F\left(\bar{e}/n - e_1\right)\Big)}{U_1\Big(F(e_1), F\left(\bar{e}/n - e_1\right)\Big)} := \tilde{\Delta}(e_1).
\end{aligned} \tag{134}$$

For convenience, we denote the first and second derivatives of the production function by $F'(e_t) = F'_t$ and $F''(e_t) = F''_t$ below. To show monotonicity we derive with respect to e_1 and obtain

$$\begin{aligned}
\frac{\mathrm{d}\tilde{\Delta}\left(e_1\right)}{\mathrm{d}e_1} &= F''_1 + F''_2\frac{U_2}{U_1} - F'_2\frac{\left[F'_1U_{21} - F'_2U_{22}\right]U_1 - \left[F'_1U_{11} - F'_2U_{12}\right]U_2}{U_1^2} \\
&= F''_1 + F''_2\frac{U_2}{U_1} - F'_2\frac{F'_1\overbrace{\left[U_{21}U_1 - U_{11}U_2\right]}^{>0} + F'_2\overbrace{\left[U_{12}U_2 - U_{22}U_1\right]}^{>0}}{U_1^2} < 0. \qquad (135)
\end{aligned}$$

This proves part 1 of Lemma 2. Note that the terms in the denominator of the second fraction in (135) are positive since c_1 and c_2 are normal goods.

Part 2: The relation of welfare to emissions We express welfare as a function of e_1, given a symmetric equilibrium and follow the approach used in (134) to express utility as a function e_1 while in the damage function we set $e_1^s = n \cdot e_1$ due to symmetry. Considering $c_t = F(e_t) - (p_t + \theta_t)e_t + \theta_t e_t + \frac{p_t e_t^s}{n} = F(e_t)$, as mentioned in the proof of part 1 of Lemma 2, it follows

$$\begin{aligned}
W\left(\theta_1, \theta_2\right) &= U\left(c_1\left(e_1, e_2\right), c_2\left(e_1, e_2\right)\right) - D\left(e_1^s\right) \\
&= U\left(F\left(e_1\right), F\left(e_2\right)\right) - D\left(ne_1\right) \\
&= U\Big(F\left(e_1\right), F\left(\bar{e}/n - e_1\right)\Big) - D\left(ne_1\right) =: \tilde{W}(e_1). \qquad (136)
\end{aligned}$$

To show single-peakedness we derive with respect to e_1, which gives

$$\frac{\mathrm{d}\tilde{W}\left(e_1\right)}{\mathrm{d}e_1} = F'_1U_1 - F'_2U_2 - nD', \qquad (137)$$

$$\lim_{e_1\to 0}\frac{\mathrm{d}\tilde{W}\left(e_1\right)}{\mathrm{d}e_1} = \underbrace{F'_1U_1}_{\infty\cdot\infty} - \underbrace{F'_2U_2}_{f^+\cdot f^+} - \underbrace{nD'}_{f^+\cdot f_0^+} > 0, \lim_{e_1\to\bar{e}/n}\frac{\mathrm{d}\tilde{W}\left(e_1\right)}{\mathrm{d}e_1} = \underbrace{F'_1U_1}_{f^+\cdot f^+} - \underbrace{F'_2U_2}_{\infty\cdot\infty} - \underbrace{nD'}_{f^+\cdot f_0^+} < 0, \qquad (138)$$

where f_0^+ (f^+) is a finite and (strictly) positive number. As we consider resource input as essential in commodity production, marginal output rises to infinity when input goes to zero. The same holds for consumption and utility.

$$\begin{aligned}
\frac{\mathrm{d}^2W\left(e_1\right)}{\mathrm{d}e_1^2} &= F''_1U_1 + F'_1\left[F'_1U_{11} - F'_2U_{12}\right] + F''_2U_2 - F'_2\left[F'_1U_{21} - F'_2U_{22}\right] - n^2D'' \\
&= \underbrace{F''_1U_1}_{<0} + \underbrace{F''_2U_2}_{<0} + \underbrace{F'^2_1U_{11}}_{<0} + \underbrace{F'^2_2U_{22}}_{<0} - \underbrace{2F'_1F'_2U_{12}}_{>0} - \underbrace{n^2D''}_{>0} < 0. \qquad (139)
\end{aligned}$$

This proves that $W(e_1)$ is a single-peaked concave function.

Carbon Fee Differentials of the Policy Equilibria

To derive the carbon fee differentials for the policy equilibrium in each scenario, we take the respective equilibrium tax rates or permit prices and replace the carbon fees by the given terms given in Propositions 1 - 3. For the case of carbon taxation we also use (103) and (104) from Appendix A. We then simplify by the use of (9) and obtain

$$\begin{aligned}\Delta(\tau_1^*, \tau_2^*) &= \tau_1^* - \frac{\tau_2^*}{1+r} = \frac{\mathfrak{N}_1}{\mathfrak{D}}\frac{D'}{U_1} - \frac{\mathfrak{N}_2}{\mathfrak{D}}\frac{\frac{D'}{U_2}}{1+r} = \left[\frac{nF_1''[1+r]}{n\mathfrak{G} - \mathfrak{F}p_1} - \frac{-nF_2''}{n\mathfrak{G} - \mathfrak{F}p_1}\right]\frac{D'}{U_1} \\ &= \underbrace{\frac{n\left[F_1''[1+r] + F_2''\right]}{n\left[\mathfrak{F}p_1 + F_1''[1+r] + F_2''\right] - \mathfrak{F}p_1}}_{=:\mathfrak{T}\,\in\,(0,1)}\frac{D'}{U_1},\end{aligned} \tag{140}$$

$$\Delta(\phi_1^*, \phi_2^*) = \phi_1(\hat{e}_1^*) - \frac{0}{1+r} = \frac{D'}{U_1}, \tag{141}$$

$$\Delta\left(\varphi_1^*|_{\alpha=0}\,, \varphi_2^*|_{\alpha=0}\right) = \varphi_1^*|_{\alpha=0} - \frac{0}{1+r} = \frac{D'}{U_1}, \tag{142}$$

$$\Delta\left(\varphi_1^*|_{\alpha=1}\,, \varphi_2^*|_{\alpha=1}\right) = \varphi_1^*|_{\alpha=1} - \frac{0}{1+r} = n\frac{D'}{U_1}, \tag{143}$$

where $\mathfrak{F} = \mathfrak{U}_1 F_1' - \mathfrak{U}_2 F_2' < 0$ with $\mathfrak{U}_v = \frac{\partial\left[\frac{U_1}{U_2}\right]}{\partial v} = \frac{U_{1v}U_2 - U_{v2}U_1}{[U_2]^2}$; $\mathfrak{U}_1 < 0$; $\mathfrak{U}_2 > 0$; $v = 1, 2$.

E Externalities

Carbon Taxation

The welfare function of country j is identical to that of country i given in (15). For sake of completeness, we also denote the dependence of the market equilibrium on domestic tax rates (j) and foreign tax rates (here $i \neq j$ as a representative foreign country)

$$W_j = U\left(c_{j1}\left(\tau_{j1}, \tau_{i1}, \tau_{j2}, \tau_{i2}\right), c_{j2}\left(\tau_{j1}, \tau_{i1}, \tau_{j2}, \tau_{i2}\right)\right) - D\left(e_1^s\left(\tau_{j1}, \tau_{i1}, \tau_{j2}, \tau_{i2}\right)\right). \tag{144}$$

We take the derivative of (144) with respect to τ_{it}, which gives

$$\frac{\partial W_j}{\partial \tau_{it}} = U_1\frac{\partial c_{j1}}{\partial \tau_{it}} + U_2\frac{\partial c_{j2}}{\partial \tau_{it}} - D'\frac{\partial e_1^s}{\partial \tau_{it}} \text{ for } t = [1, 2]. \tag{145}$$

Equations (76) and (77) carry over to country j. So, we divide these by $\mathrm{d}\tau_{it}$ and use the resulting expressions for $\frac{\partial c_{j1}}{\partial \tau_{it}}$ and $\frac{\partial c_{j2}}{\partial \tau_{it}}$ in (145). Then we simplify by use of (5), (9), and the symmetry assumption as stated in Section 2 and obtain

$$\frac{\partial W_j}{\partial \tau_{it}} = U_1\tau_{j1}\frac{\partial e_{j1}}{\partial \tau_{it}} + U_2\tau_{j2}\frac{\partial e_{j2}}{\partial \tau_{it}} - D'\frac{\partial e_1^s}{\partial \tau_{it}} \text{ for } t = [1, 2]. \tag{146}$$

In order to evaluate (146) at the policy equilibrium, we use (17) and (18) together with (103) and (104) as well as the relevant expressions from (95) - (97), which gives

$$\frac{\partial W_j}{\partial \tau_{i1}} = \underbrace{U_1 \tau_1^* \frac{\partial e_{j1}}{\partial \tau_{i1}}}_{LE1_{ij}(+)} + \underbrace{U_2 \tau_2^* \frac{\partial e_{j2}}{\partial \tau_{i1}}}_{LE2_{ij}(-)} \underbrace{- D' \frac{\partial e_1^s}{\partial \tau_{i2}}}_{EE_{ij}(+)}$$

$$\frac{\partial W_j}{\partial \tau_{i1}} = D' \Bigg[\underbrace{\frac{-\mathfrak{F} p_1}{\mathfrak{G}[n\mathfrak{G} - \mathfrak{F} p_1]}}_{LE_{ij}(+)} + \underbrace{\frac{-[1+r]}{\mathfrak{G}}}_{EE_{ij}(+)} \Bigg] > 0. \tag{147}$$

as well as

$$\frac{\partial W_j}{\partial \tau_{i2}} = \underbrace{U_1 \tau_1^* \frac{\partial e_{j1}}{\partial \tau_{i2}}}_{LE1_{ij}(+)} + \underbrace{U_2 \tau_2^* \frac{\partial e_{j2}}{\partial \tau_{i2}}}_{LE2_{ij}(-)} \underbrace{- D' \frac{\partial e_1^s}{\partial \tau_{i2}}}_{EE_{ij}(-)}$$

$$\frac{\partial W_j}{\partial \tau_{i2}} = D' \Bigg[\underbrace{\frac{\mathfrak{F} p_1}{\mathfrak{G}[n\mathfrak{G} - \mathfrak{F} p_1]}}_{LE_{ij}(-)} + \underbrace{\frac{1}{\mathfrak{G}}}_{EE_{ij}(-)} \Bigg] < 0. \tag{148}$$

Cap-and-Trade Policy

Local permit markets The change in consumption in country j due to change in $\hat{e}_{i1}$ is derived along the lines of Appendix B, see (108) and (109), only that $\mathrm{d}\hat{e}_{j1} = 0$.

$$\frac{\partial c_{j1}}{\partial \hat{e}_{i1}} = \left[F_1' - p_1 - \phi_{i1}\right] \underbrace{\frac{\partial \hat{e}_{j1}}{\partial \hat{e}_{i1}}}_{=0} - \left[\frac{\partial p_1}{\partial \hat{e}_{i1}} + \frac{\partial \phi_{i1}}{\partial \hat{e}_{i1}}\right] \hat{e}_{j1} + \frac{\partial \phi_{j1}}{\partial \hat{e}_{i1}} \hat{e}_{j1} + \frac{1}{n}\Bigg[p_1 \underbrace{\frac{\partial e_1^s}{\partial \hat{e}_{i1}}}_{=1} + e_1^s \frac{\partial p_1}{\partial \hat{e}_{i1}}\Bigg] + \frac{\partial b_i}{\partial \hat{e}_{i1}}$$

$$\frac{\partial c_{j1}}{\partial \hat{e}_{i1}} = \frac{p_1}{n} + \frac{\partial b_i}{\partial \hat{e}_{i1}}, \tag{149}$$

$$\frac{\partial c_{j2}}{\partial \hat{e}_{i1}} = \Bigg[\underbrace{F_2' - p_2}_{=0}\Bigg] \cdot \frac{\partial e_{i2}}{\partial \hat{e}_{i1}} - e_{i2} \frac{\partial p_2}{\partial \hat{e}_{i1}} + \frac{1}{n}\Bigg[p_2 \underbrace{\frac{\partial e_2^s}{\partial \hat{e}_{i1}}}_{=-1} + e_2^s \frac{\partial p_2}{\partial \hat{e}_{i1}}\Bigg] - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i1}} - \underbrace{b_i}_{=0} \frac{\partial r}{\partial \hat{e}_{i1}}$$

$$\frac{\partial c_{j2}}{\partial \hat{e}_{i1}} = -\frac{p_2}{n} - [1+r]\frac{\partial b_i}{\partial \hat{e}_{i1}}. \tag{150}$$

Along the lines of the derivation of external effects of carbon taxation (see above here) the welfare function of country j depending on domestic caps (j) and foreign caps (here $i \neq j$) writes

$$W_j = U\Big(c_{j1}\left(\hat{e}_{j1}, \hat{e}_{i1}\right), c_{j2}\left(\hat{e}_{j1}, \hat{e}_{i1}\right)\Big) - D\Big(e_1^s\left(\hat{e}_{j1}, \hat{e}_{i1}\right)\Big). \tag{151}$$

We take the derivative of (151), plug in (149) and (150) and simplify by making use of (5) and (9) to obtain

$$\frac{\partial W_j}{\partial \hat{e}_{i1}} = U_1 \frac{\partial c_{j1}}{\partial \hat{e}_{i1}} + U_2 \frac{\partial c_{j2}}{\partial \hat{e}_{i1}} - D' \frac{\partial e_1^s}{\partial \hat{e}_{i1}}, \tag{152}$$

$$\frac{\partial W_j}{\partial \hat{e}_{i1}} = \underbrace{-D'}_{EE_{ij}} < 0. \tag{153}$$

Linked permit markets As for local permit markets, we begin by deriving $\frac{\partial c_{j1}}{\partial \check{e}_{i1}}$ and $\frac{\partial c_{j2}}{\partial \check{e}_{i1}}$. We follow the derivation of (121) and (122), where we still have $\mathrm{d}\check{e}_{i1} \neq 0$ and $\mathrm{d}\check{e}_{j1} = 0$ and where $T_{j1} = \varphi_1 \check{e}_{j1}$ and $T_{j2} = 0$ and obtain

$$\frac{\partial c_{j1}}{\partial \check{e}_{i1}} = \frac{\alpha}{n}\varphi_1 + \frac{p_1}{n} + \frac{\partial b_j}{\partial \check{e}_{i1}}, \tag{154}$$

$$\frac{\partial c_{j2}}{\partial \check{e}_{i1}} = -\frac{p_2}{n} - [1+r]\frac{\partial b_j}{\partial \check{e}_{i1}}. \tag{155}$$

Then, adapting (151) to the scenario of linked permit markets gives

$$W_j = U\Big(c_{j1}\left(\check{e}_{j1}, \check{e}_{i1}\right), c_{j2}\left(\check{e}_{j1}, \check{e}_{i1}\right)\Big) - D\Big(e_1^s\left(\check{e}_{j1}, \check{e}_{i1}\right)\Big), \tag{156}$$

which we derive with respect to $\check{e}_{i1}$ to obtain

$$\frac{\partial W_j}{\partial \check{e}_{i1}} = U_1 \frac{\partial c_{j1}}{\partial \check{e}_{i1}} + U_2 \frac{\partial c_{j2}}{\partial \check{e}_{i1}} - D' \frac{\partial e_1^s}{\partial \check{e}_{i1}}. \tag{157}$$

Lastly, we use (154) and (155) in (157) and simplify with the help of (5) and (9) to receive

$$\frac{\partial W_j}{\partial \check{e}_{i1}} = \frac{\alpha}{n} U_1 \varphi_1(\check{e}_1^*) - D'. \tag{158}$$

Otto von Guericke University Magdeburg
Faculty of Economics and Management
P.O. Box 4120 | 39016 Magdeburg | Germany

Tel.: +49 (0) 3 91 / 67-1 85 84
Fax: +49 (0) 3 91 / 67-1 21 20

www.fww.ovgu.de/femm

ISSN 1615-4274